Better Decisions, Better Products
Through Simulation & Innovation

"Advanced 3D Modeling and Simulations to Improve Designs of Active Pixel CMOS Sensors for Charged Particle Detection"

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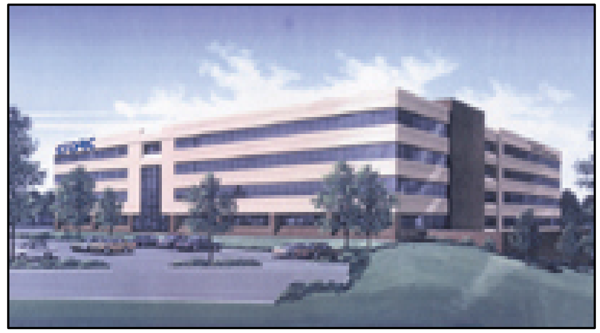
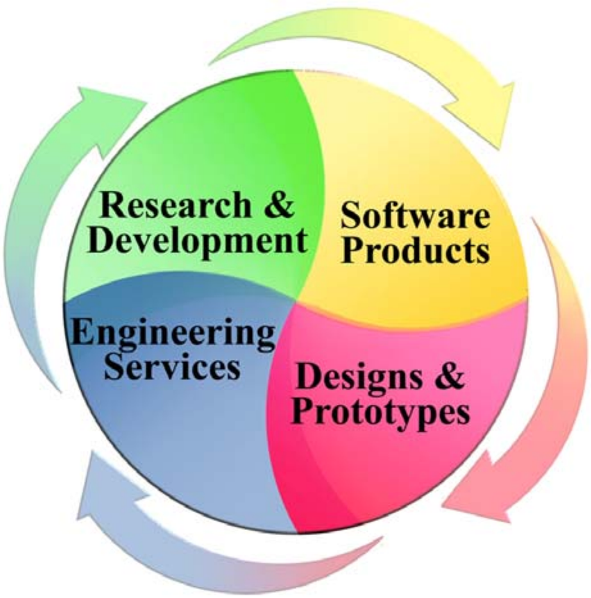
* The tools and results supported by **DARPA** RadHard-By-Design Program, **AFRL**/Space Vehicles Directorate, **DTRA**, **NASA**, and **ATK Mission Research**

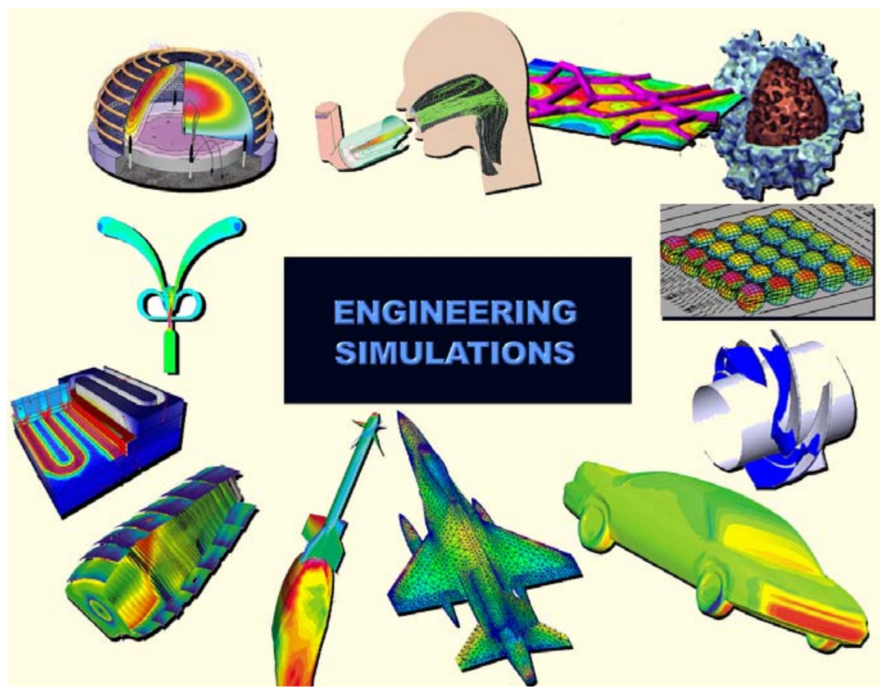
Presented at BNL - November 30, 2005

Better Decisions, Better Products Through Simulation & Innovation

- 90 People (60% PhD's) in R&D Offices in Huntsville, AL
- Steady Growth since inception (1987)

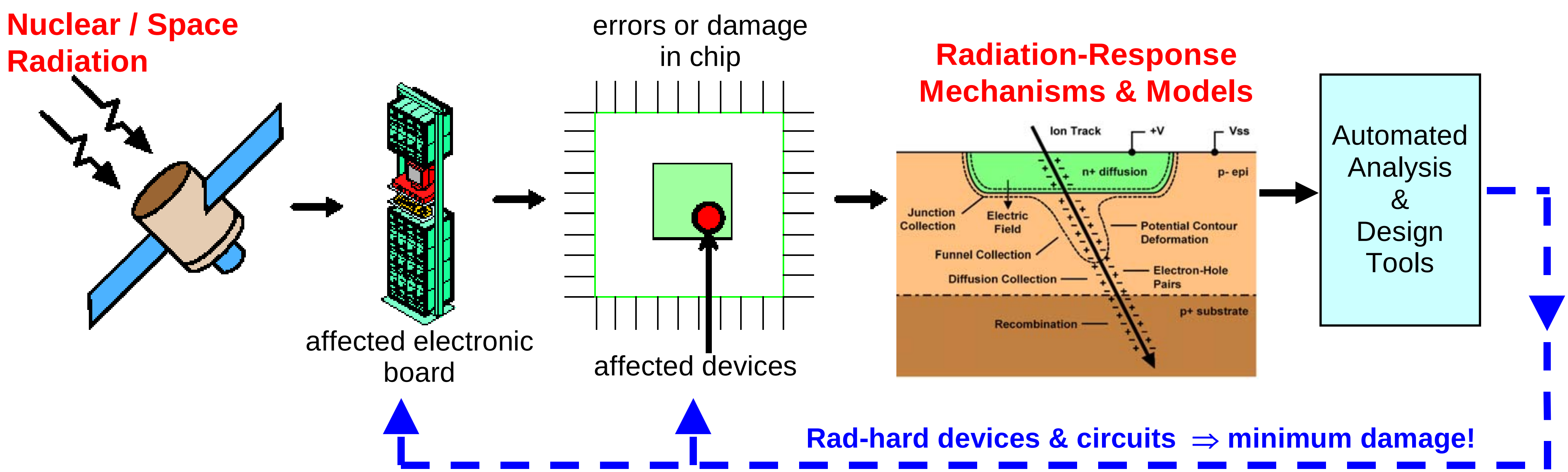




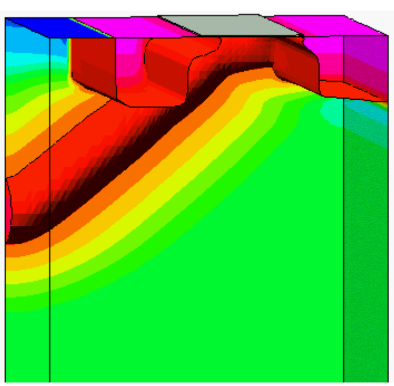


- **R&D Sponsors:** DoD, DoE, NASA, NIH, NIST, NSF, and Industry
- **Customers:** Over 500 worldwide
- **Collaborators:** Over 30 research organizations, universities

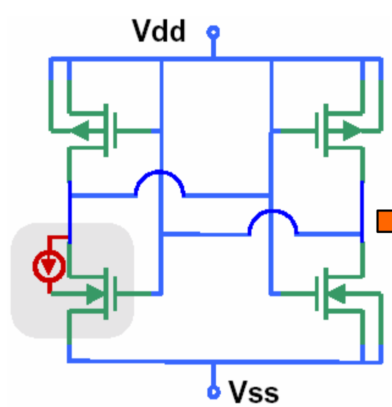
Hierarchical CAD Tools for Radiation-Hardening by Design (RHBD)



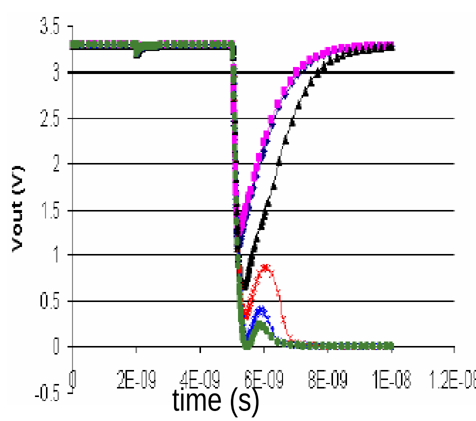
3D Device Simulation



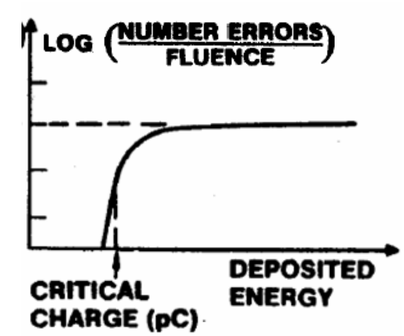
Mixed-Mode or Circuit Model



Signal "Upset"

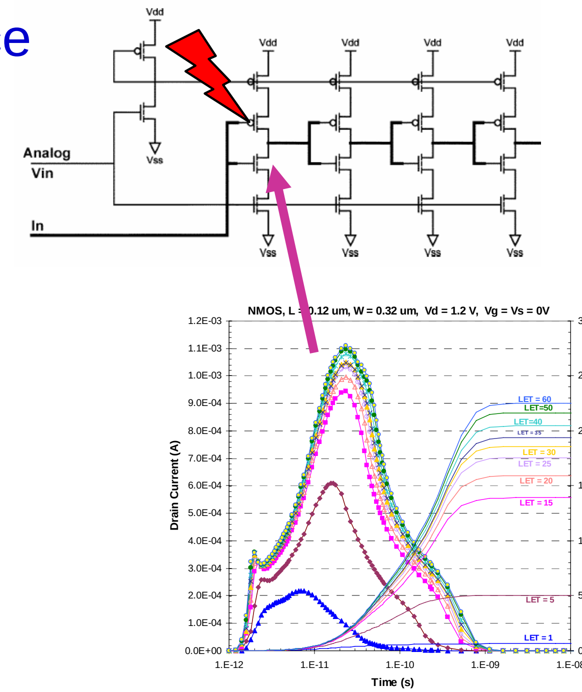


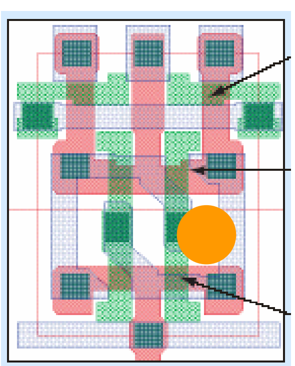
CHIP CROSS SECTION (cm^2) (Sensitivity to Radiation)

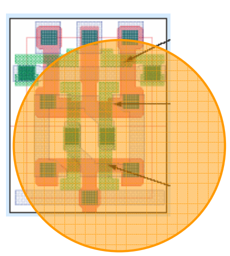


Issues for Nanoscale ICs

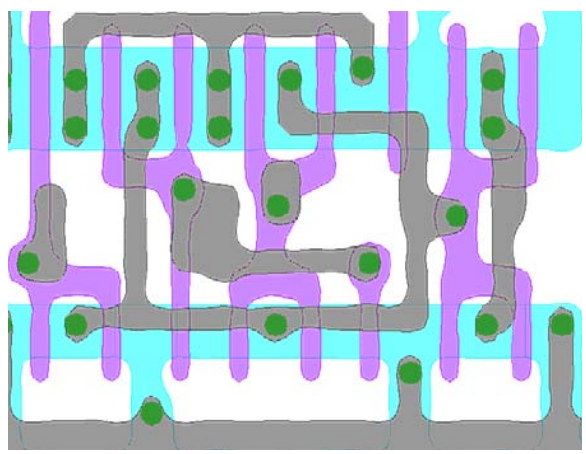
- **Single Event Transients (SET)** are of increasing importance as device sizes shrink and operating frequencies grow
  ⇒ Mixed-Mode Simulation becomes more important
- **SE Pulse analytical models** (Spice EXP) not good enough
  ⇒ require 3D TCAD - to determine pulse shape
- **Secondary particles, recoils, collisions…**
  ⇒ need more accurate SE models (Geant4, etc…)
- **More complex layout shapes (OPC); quantum physics**
  ⇒ require improved 3D tools
- **Ion track area may cover multiple DSM devices**
  ⇒ required 3D modeling of larger structures
  ⇒ … need Parallel Solver



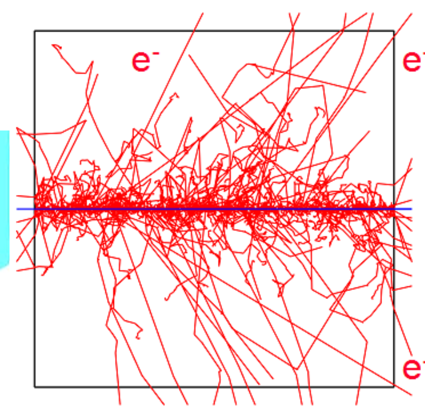




Ion Track Diameter covers more …



Mentor Graphics, RET



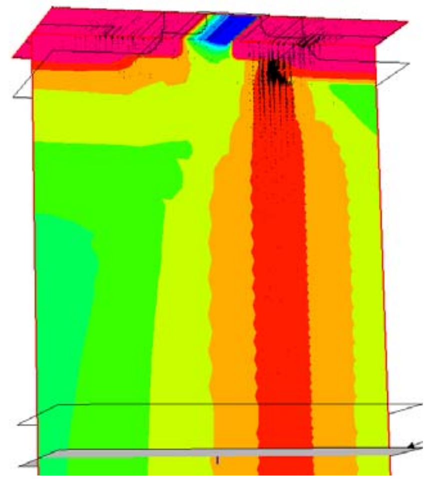
Vanderbilt U.

Current Joint Program of CFDRC and ISDE/VU

“Improved Understanding of Space Radiation Effects in Exploration Electronics by Advanced Modeling of Nanoscale Devices and Novel Materials”

STTR Phase I Project, sponsored by **NASA** Ames (2005):

- **CFD Research Corporation:** M. Turowski (PI), A. Fedoseyev, A. Raman
- **ISDE-Vanderbilt University:** M. Alles, R. Weller, R. Schrimpf

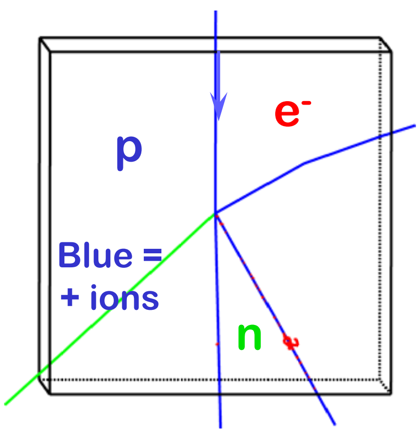


3D device simulation

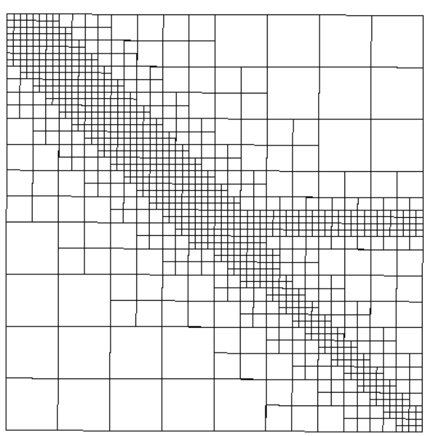
Program Objectives:

- **Couple** Vanderbilt **Geant4 and** CFDRC **NanoTCAD 3D Device Solver**
- **Adaptive/dynamic 3D meshing** for multiple ion tracks
- **Statistically meaningful** runs on a **massively parallel computing cluster**
- **Integrated and automated** interface of **Geant4** and **CFDRC NanoTCAD**

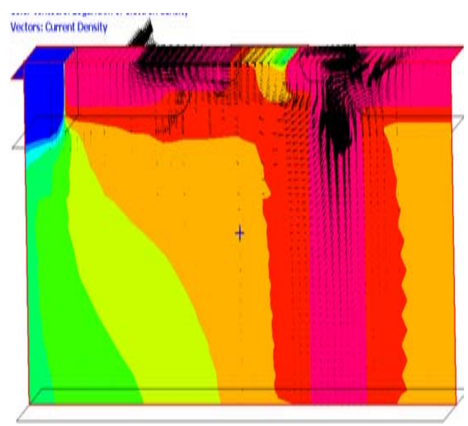
Geant4
- accurate model of radiation event



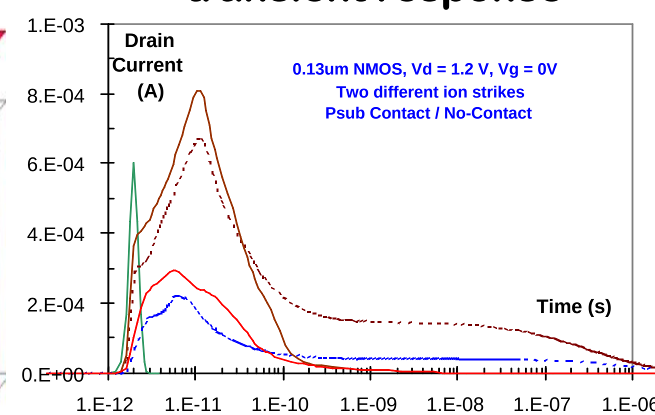
- Adaptive 3D meshing



- 3D Nanoscale transport



- Physics based transient response



Joint SBIR of CFDRC and ISDE/VU

"Improved Mixed-Mode Simulation Tools for Radiation Hardening of Nanoscale Semiconductor Integrated Circuits"

Vanderbilt University

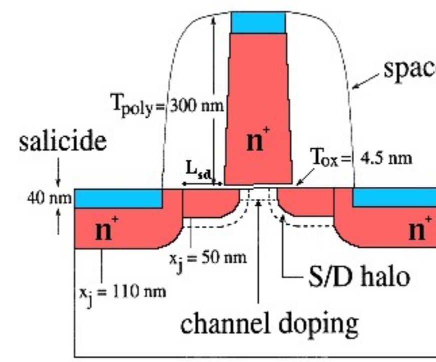
SBIR Phase I Project (2005), sponsored by **DTRA** (L. Cohn)

- **CFD Research Corporation:** M. Turowski (PI), A. Raman, A. Fedoseyev
- **ISDE-Vanderbilt University:** M. Alles, R. Schrimpf
- Collaborators: **Mentor Graphics**: M. Bazel; **Honeywell**: J. Yue

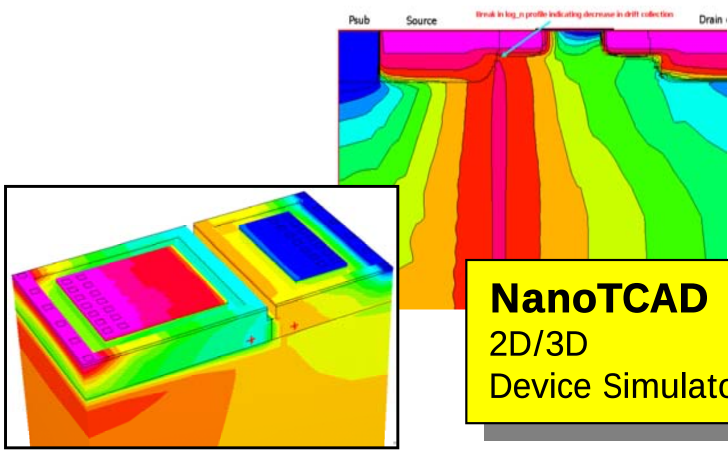
Program Objectives:

- Add **nano/quantum physics** to *NanoTCAD* for **sub-100-nm devices**
- **Automated** generation of **3D simulation models from IC layouts**
- **Efficient Mixed-Mode** simulator coupling **CFDRC *NanoTCAD* 3D device simulator** with **upgraded Berkeley *SPICE*** (incl. BSIM4, BSIMSOI, etc.)
- Interfaces with **advanced behavioral/system simulators**: ***ELDO*** from **Mentor Graphics**, and the ***ModLyng*** high-level models from **Lynguent**.

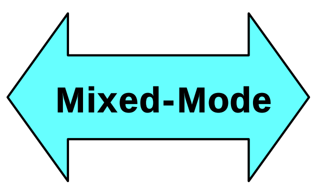
Sub-100-nm Devices…



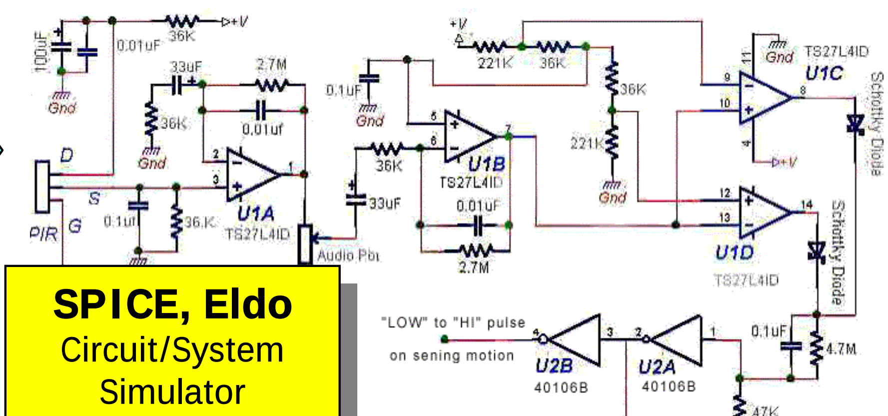
3D Nano-Scale Device Models…



NanoTCAD
2D/3D
Device Simulator



… with Full External Circuit Interaction

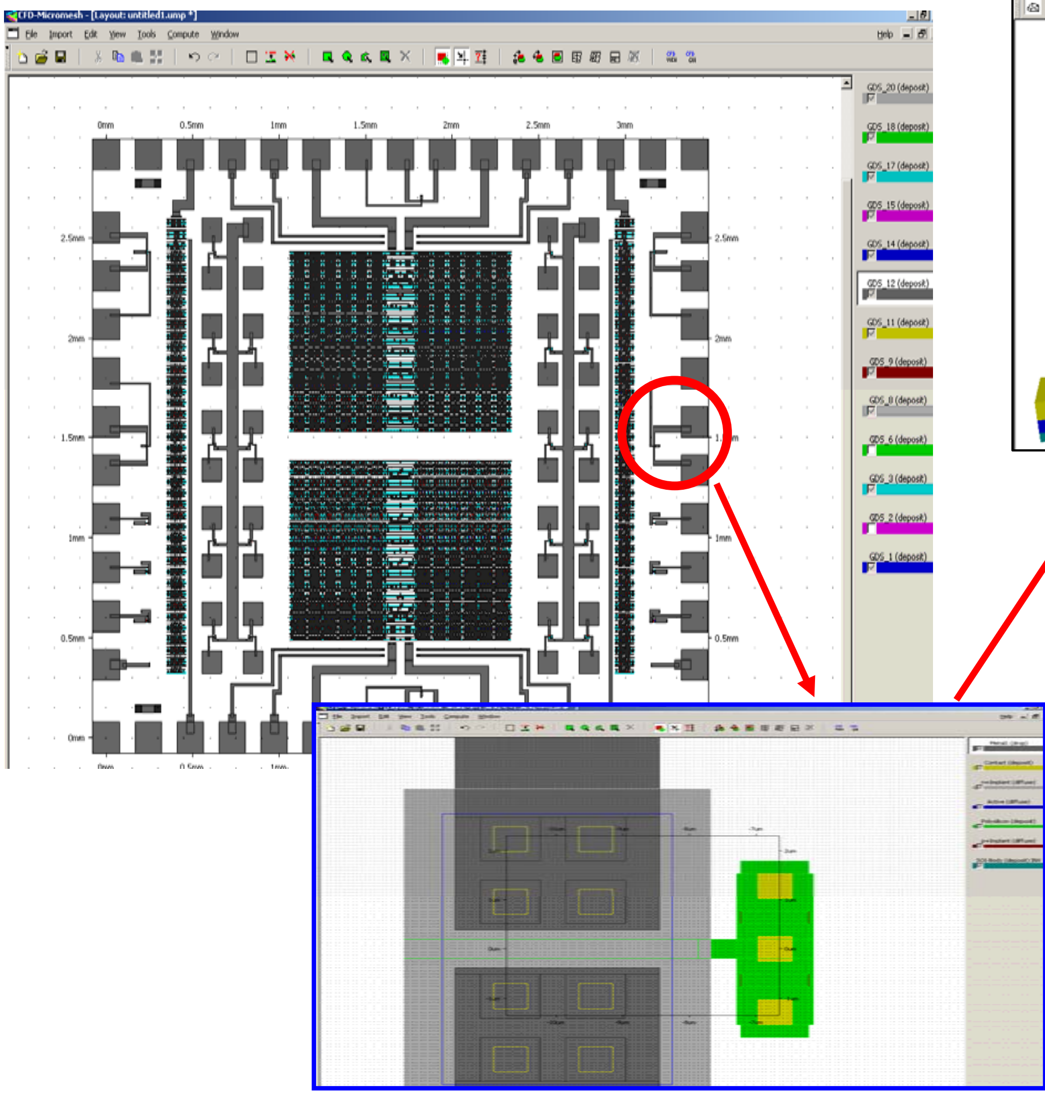


SPICE, Eldo
Circuit/System
Simulator

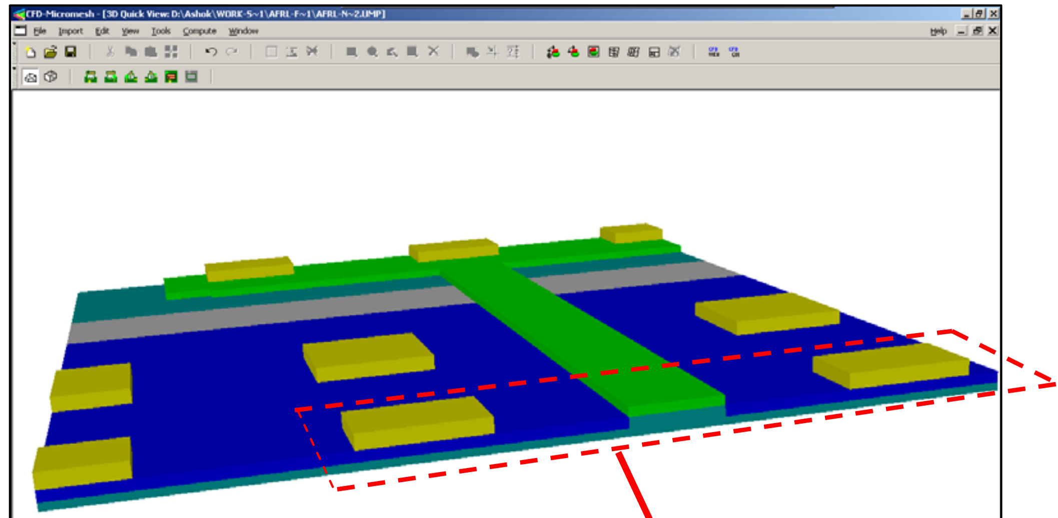
CFDRC *NanoTCAD*

IC Layout ➔ 3D Model ➔ 3D Mesh ➔ Simulation

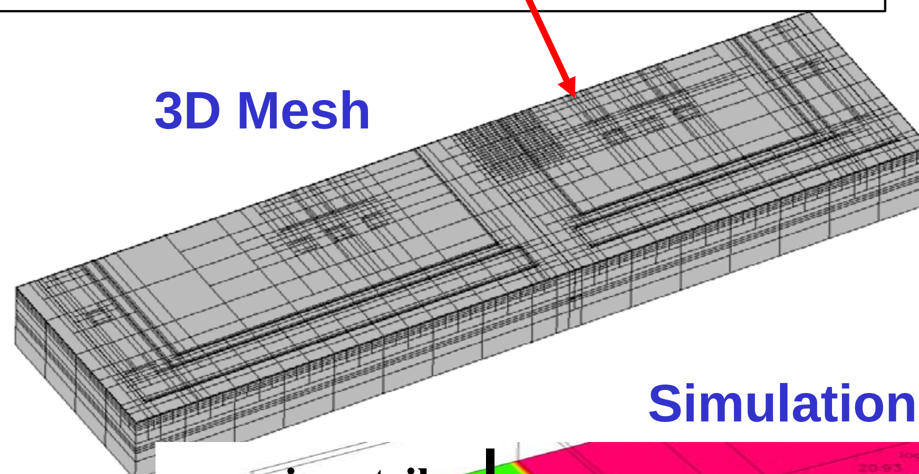
Imported Layout
(GDSII, CIF, DXF, GIF)



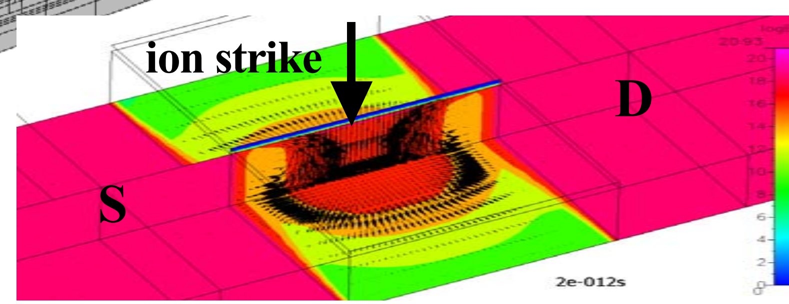
Automatic Generation of 3D Model



3D Mesh



Simulation

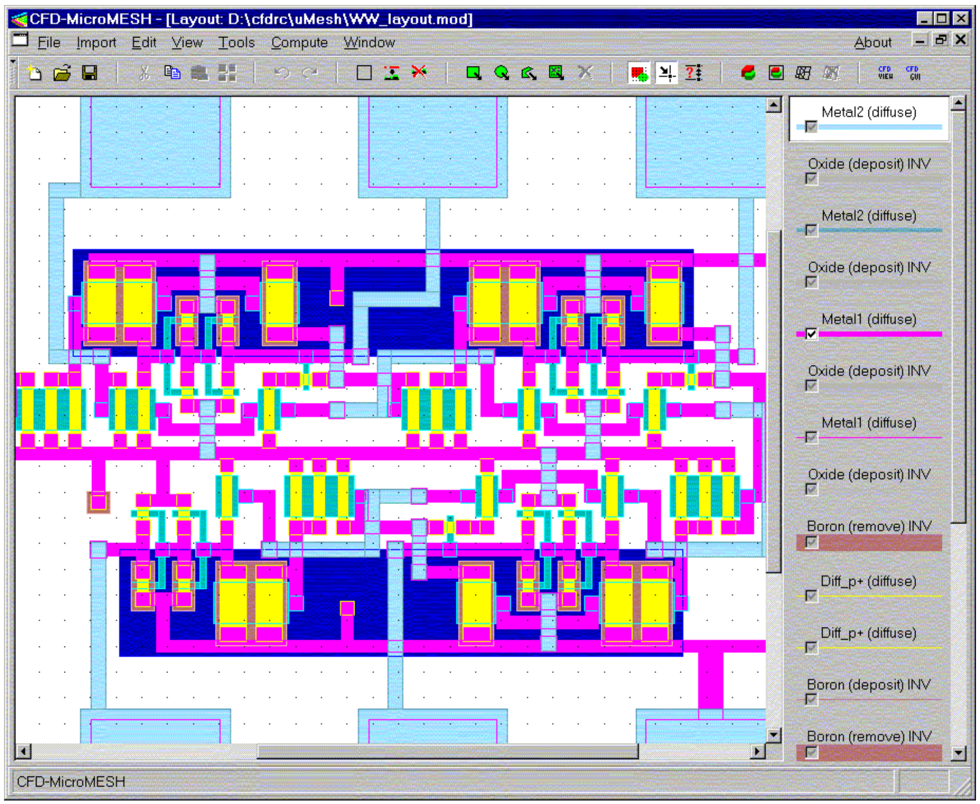


Mask Layout ➔ 3D Solids ➔ Meshed Model

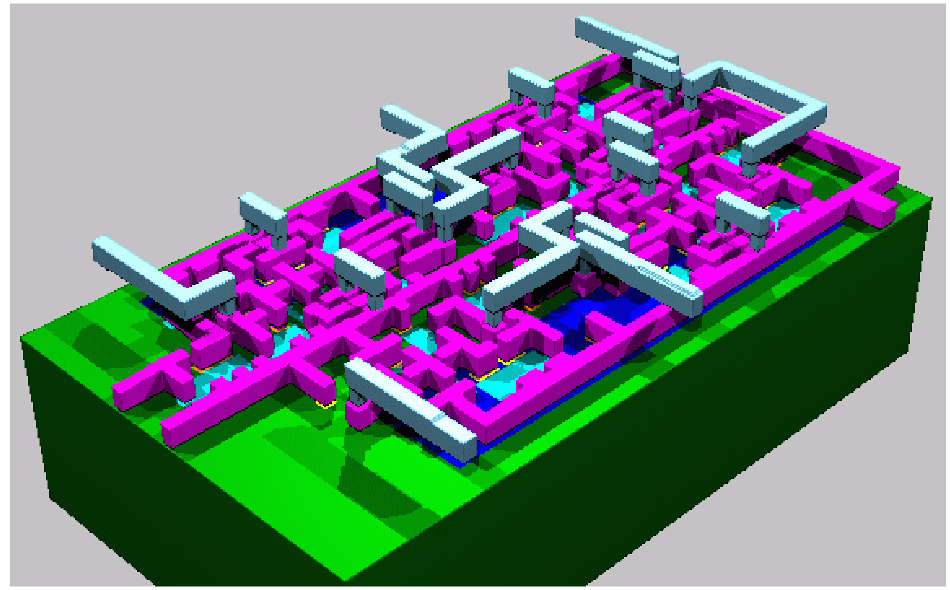
Micromesh

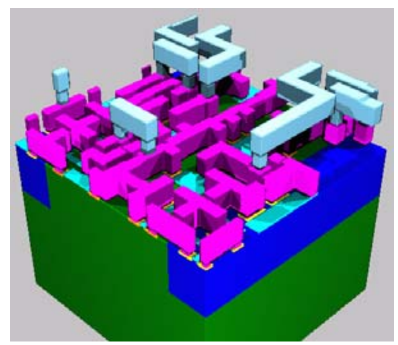
Layout Editor

+ imports: GDSII, CIF, DXF

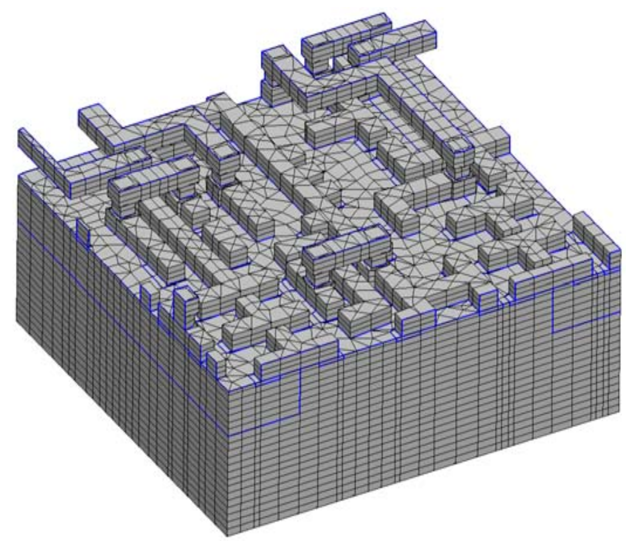


Automatic Generation of 3D Model





Automatic 3D Mesh



NanoTCAD Solver from CFDRC

Full 3-D Semiconductor Device Simulator, based on <u>Drift-Diffusion (DD) or Hydrodynamic (HD) Semiconductor Models:</u>

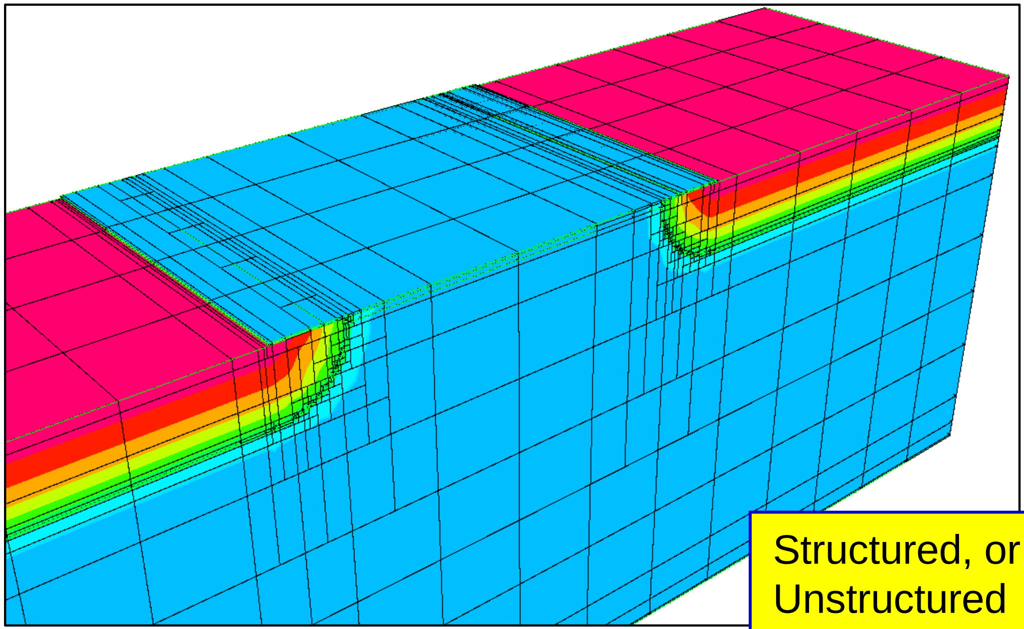
Electric Potential Equation

$$\nabla \cdot \left(-\varepsilon \nabla \phi\right) = q\left(p - n + N_D^+ - N_A^-\right)$$

Carrier Continuity Equations

$$q\frac{\partial n}{\partial t} - \nabla \cdot \vec{J}_n = q(G - R)$$

$$q\frac{\partial p}{\partial t} + \nabla \cdot \vec{J}_p = q(G - R)$$



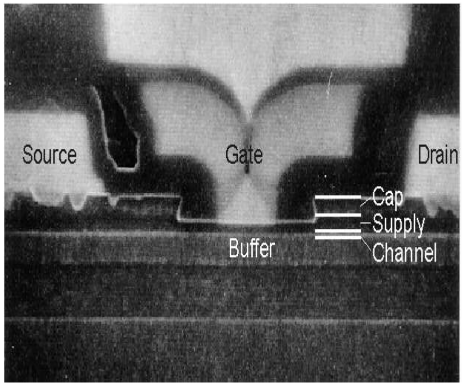
Structured, or Unstructured Meshes

where current densities are:

$$\vec{J}_n = qD_n \nabla n + qn\left\{\mu_n \nabla\left(-\phi + \frac{E_c}{q}\right) + D_n \nabla T_n - \frac{3}{2} D_n \nabla \ln m_n\right\}$$

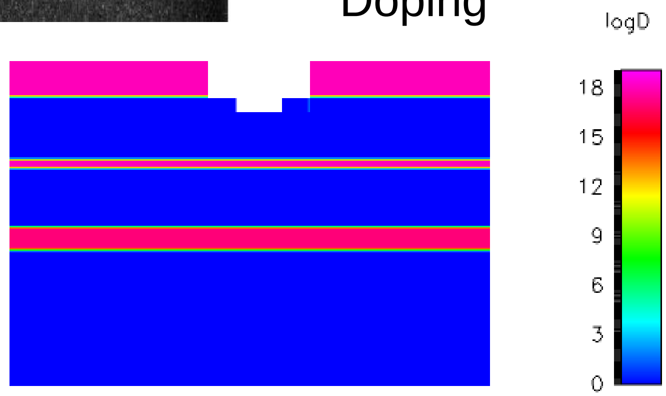
$$\vec{J}_p = -qD_p \nabla p + qp\left\{\mu_p \nabla\left(-\phi + \frac{E_v}{q}\right) + D_p \nabla T_p - \frac{3}{2} D_p \nabla \ln m_p\right\}$$

Modeling Heterostructure Devices (HEMT, HBT, …) in *NanoTCAD*

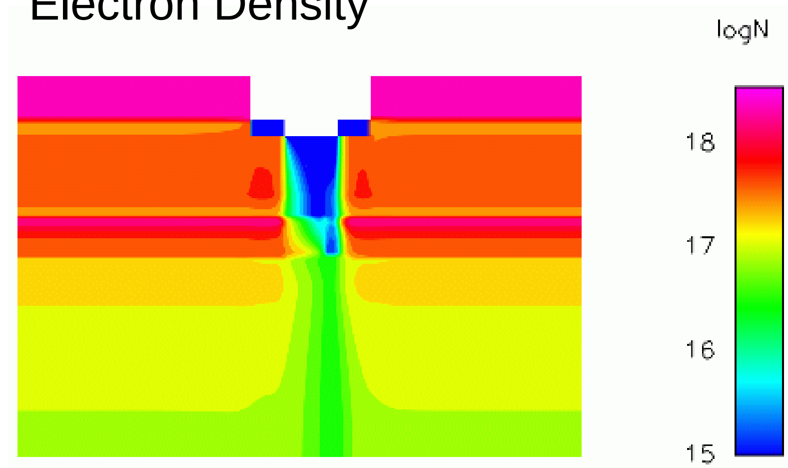


Hydrodynamic (HD) Simulation of Submicron AlGaAs/InGaAs pseudomorphic HEMT (pHEMT)

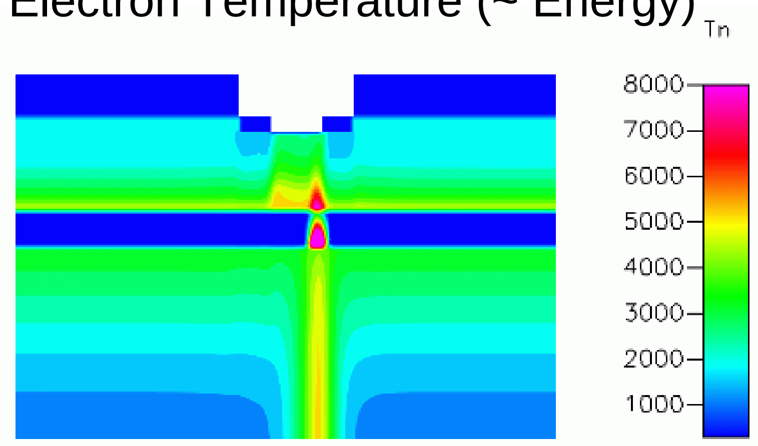
Doping



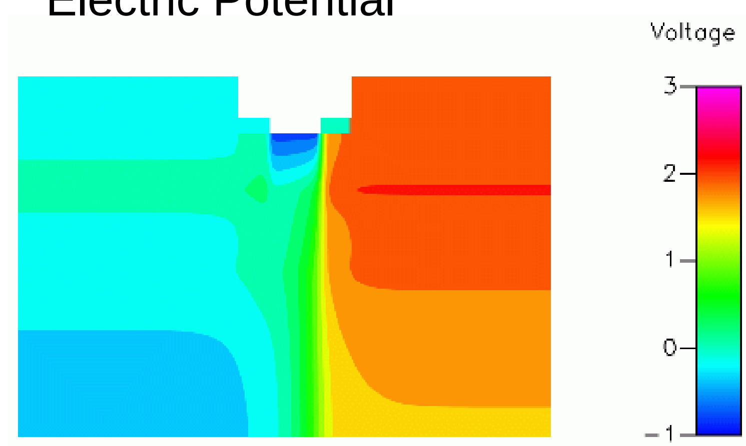
Electron Density



Electron Temperature (~ Energy)



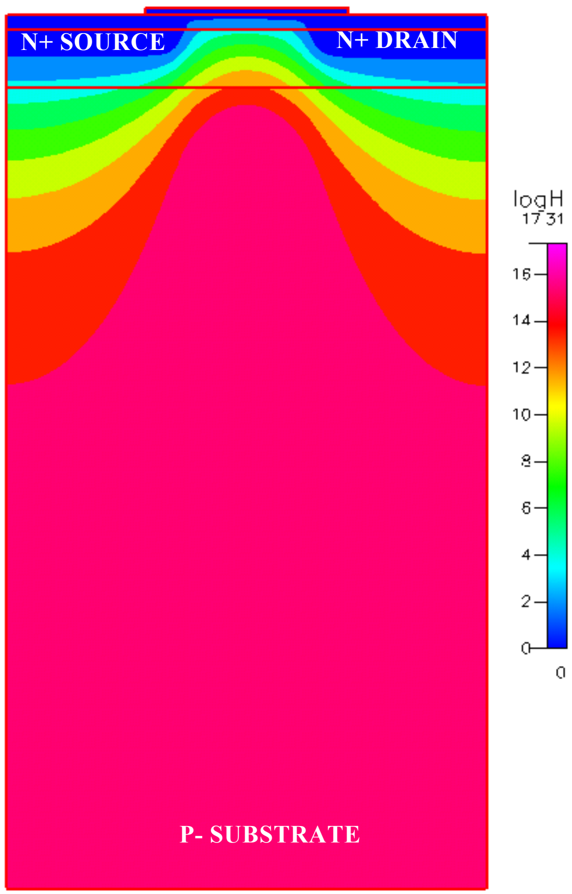
Electric Potential

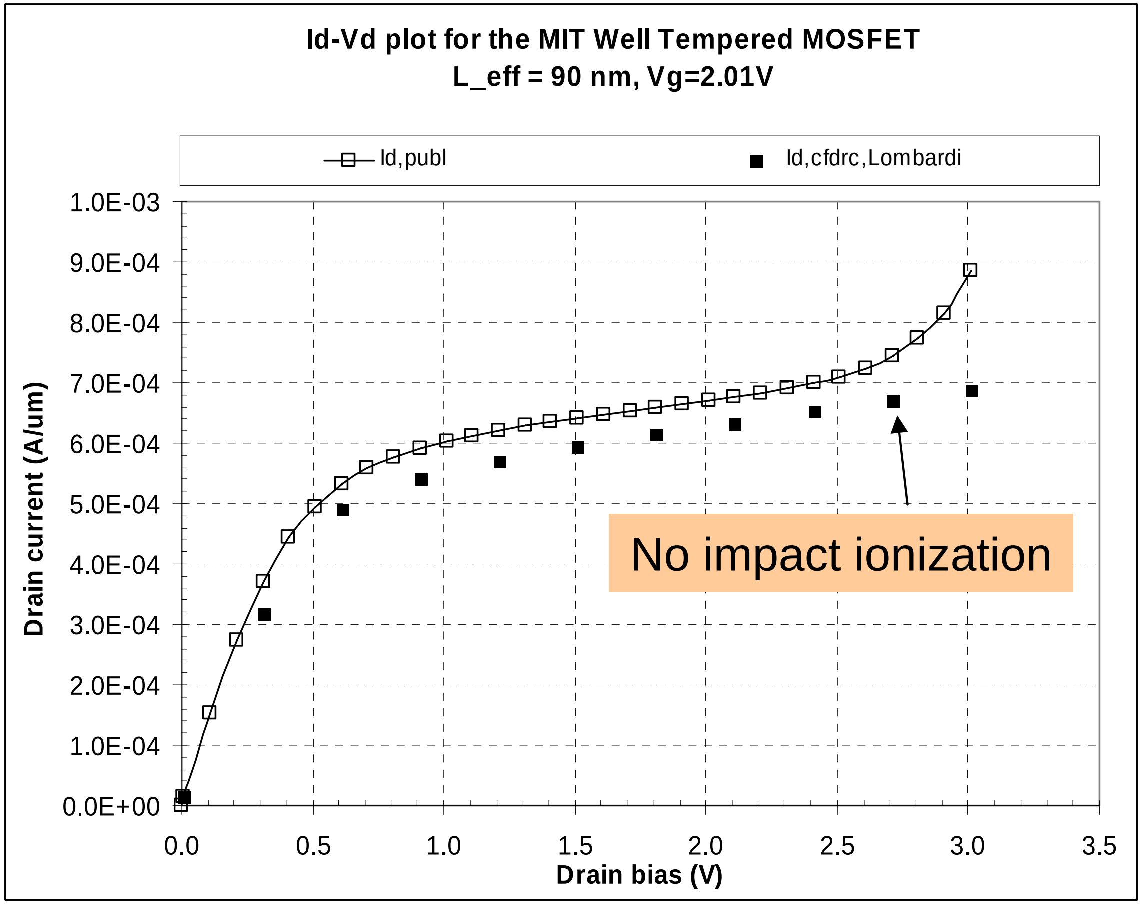


Validation Example: MIT 90-nm MOSFET

- 2D well-tempered NMOSFET

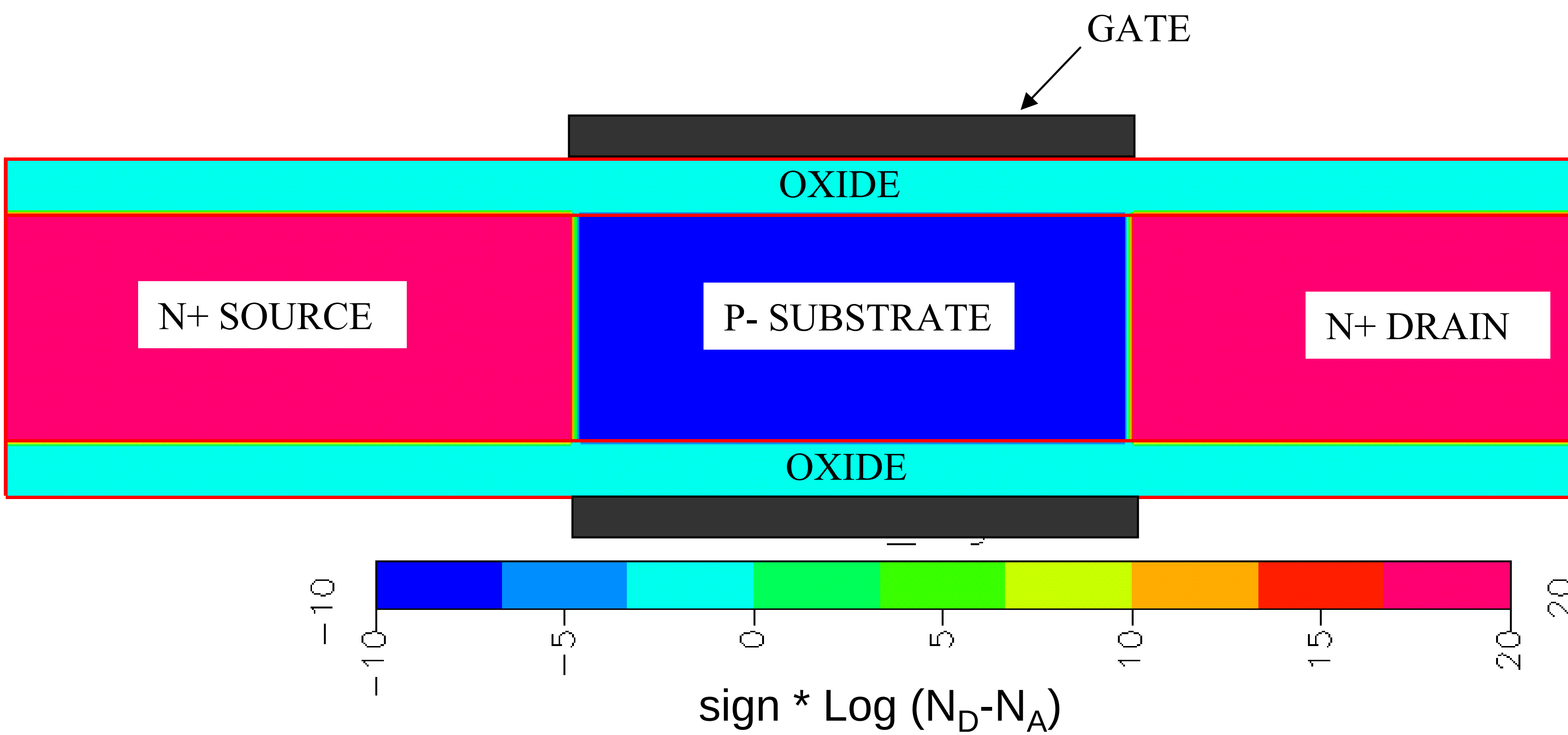
  (source: www-mtl.mit.edu/Well/) - Microsystems Technology Lab (MTL) of MIT
- Designed to be benchmarks for “next generation” simulators
- L_{eff} = 90 nm, depth = 600 nm





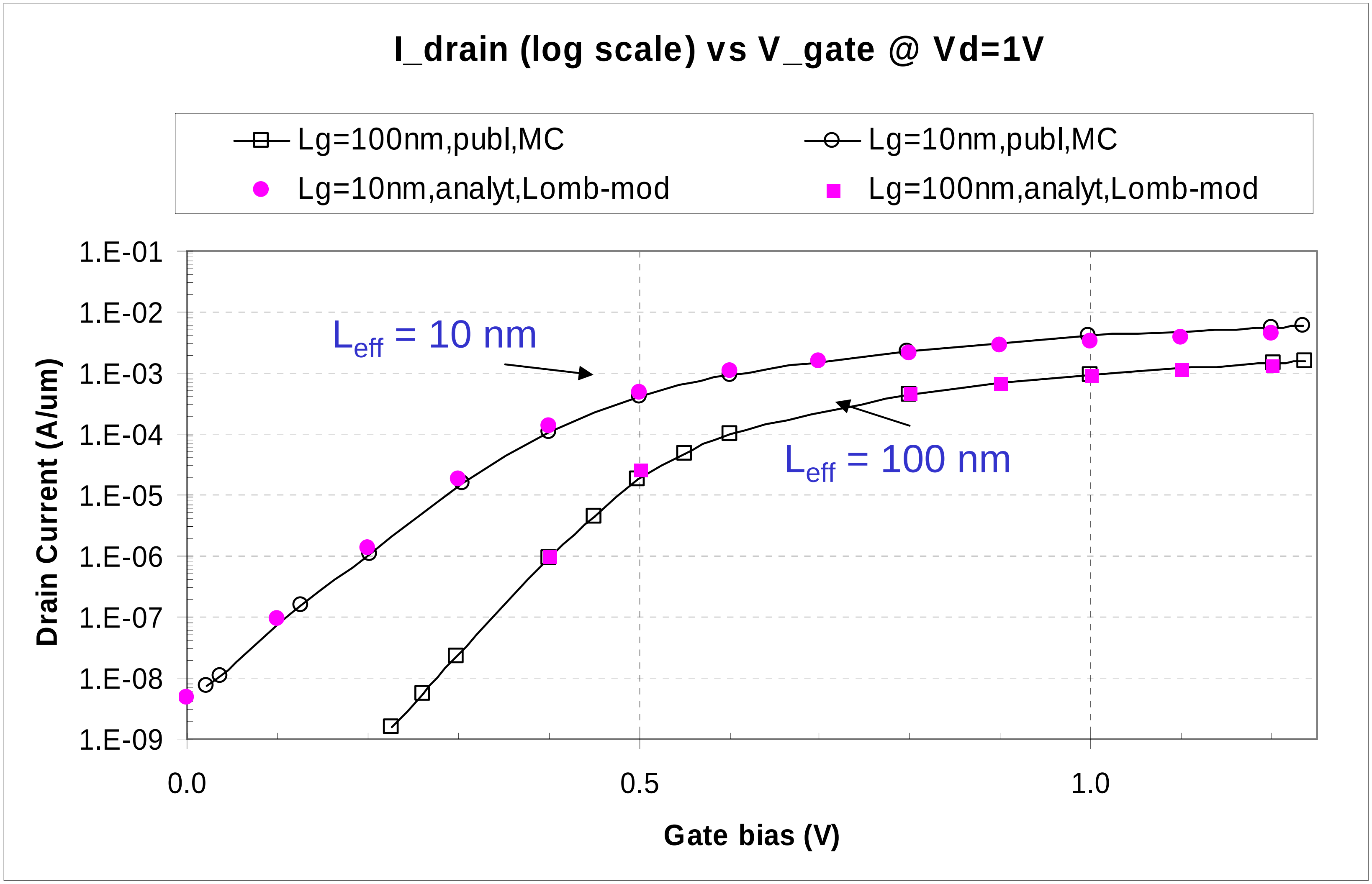
Validation Example: DG MOSFET

- **Double-Gate** (**DG**) **nMOSFET** from *Granzner et al., 2003*
- **Channel** L_{eff} (case-1) = **100 nm**, L_{eff} (case-2) = **10 nm**
- t_{ox} = 1 nm



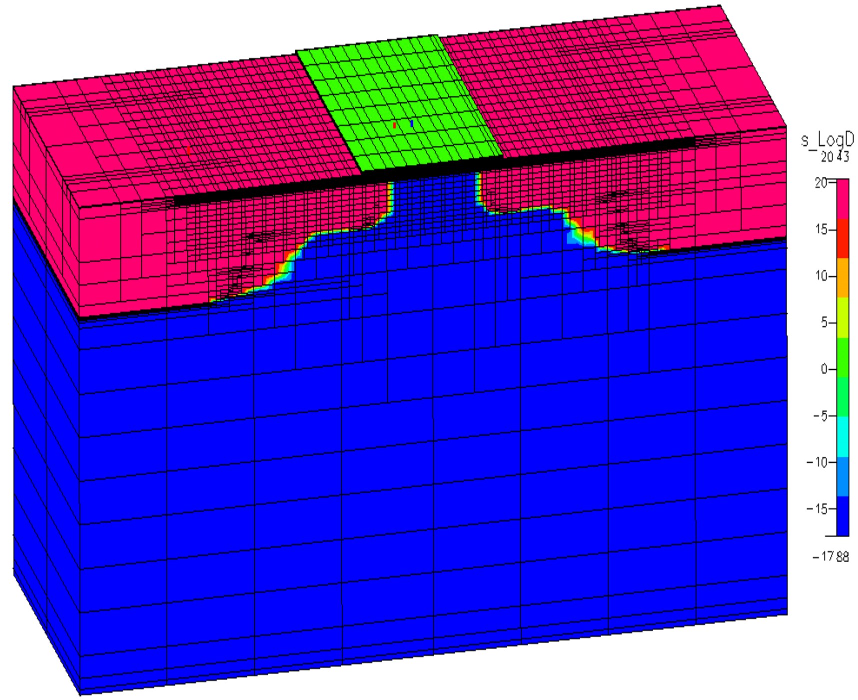
Validation Example: DG MOSFET (cont.)

Sub-threshold behavior for L_{eff} = 10 nm and 100 nm



Important: Drift-diffusion model is applicable even in the deep submicron regime !!!

Cell Layout ➔ 3D Device Model

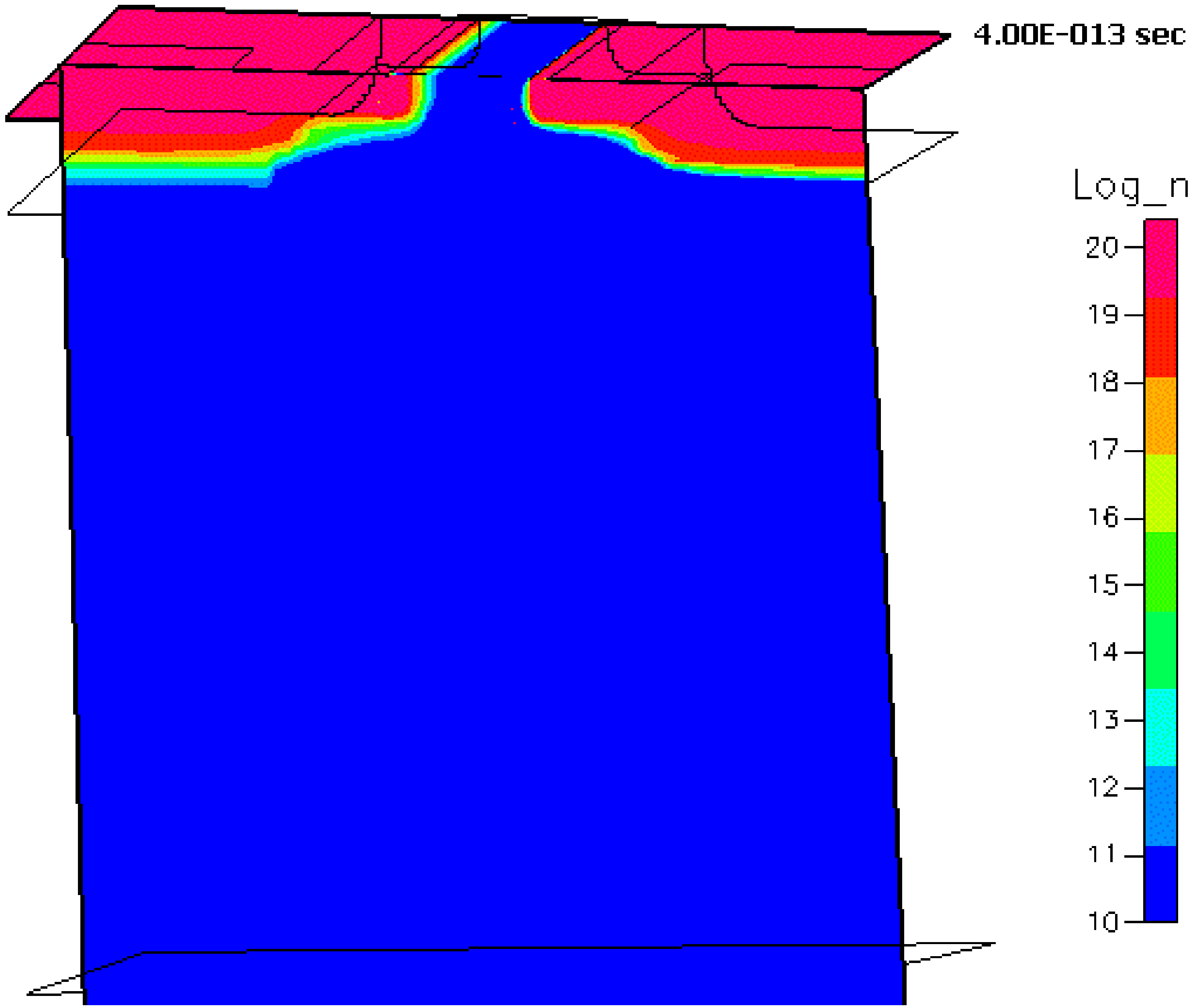


GDSII layout from ATK-MR

"Equivalent" 3D model of NFET
L = 0.12 µm, W = 0.5 µm

Single-Event Modeling in 120-nm NMOS

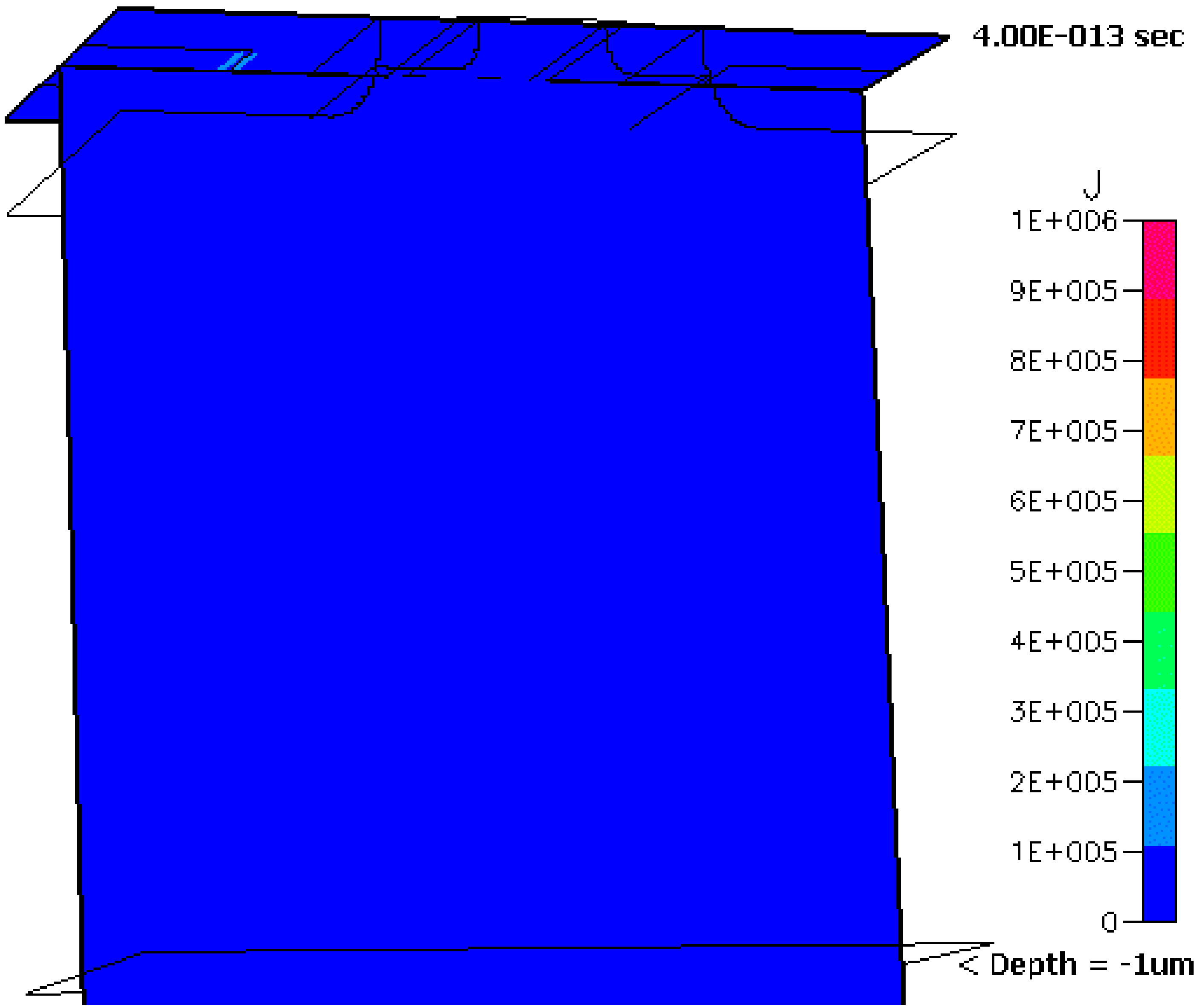
↓ **Color map: Electron Density, Log(n)**



Single-Event Modeling in 120-nm NMOS

- Prompt Charge Collection Depth Analysis

↓ Color map: Local Current Density, J



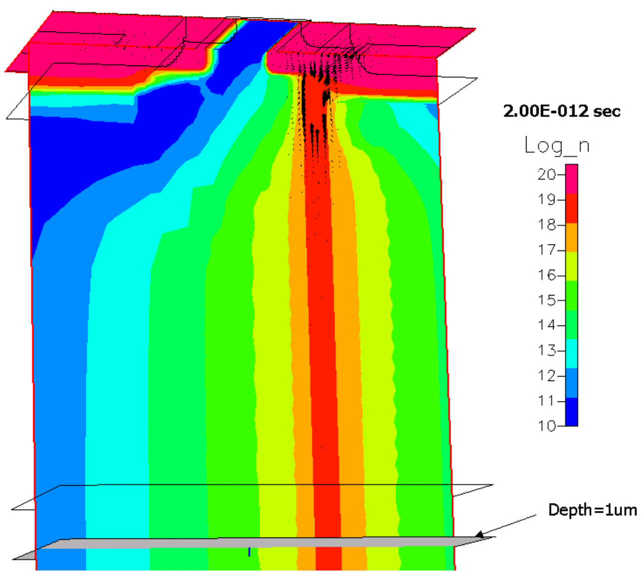
Single-Event Modeling Results

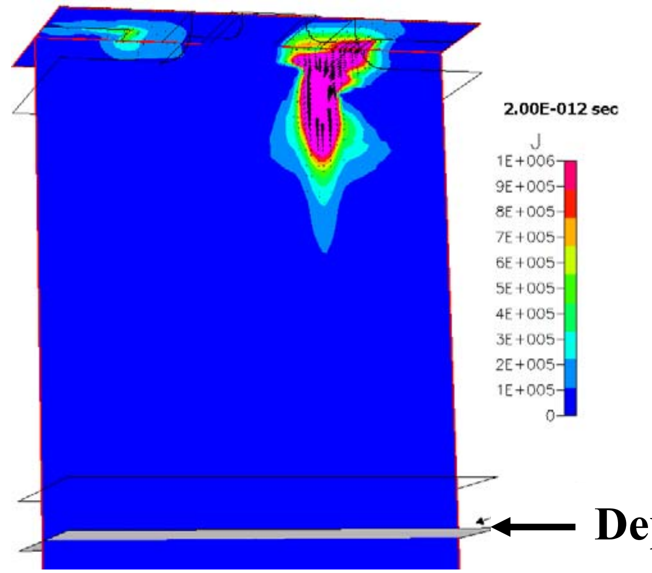
- Prompt Charge Collection Depth Analysis

↓ Color map: Electron Density, Log(n)

↓ Color map: Local Current Density, J

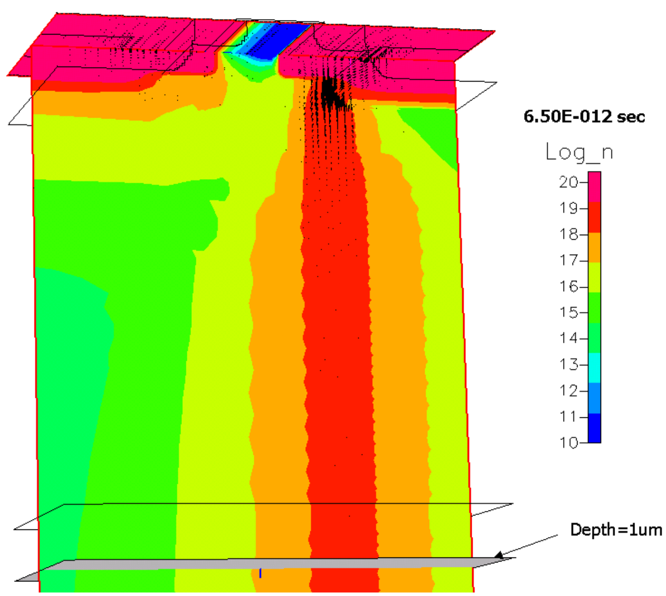
time = 2 ps
(ion max)

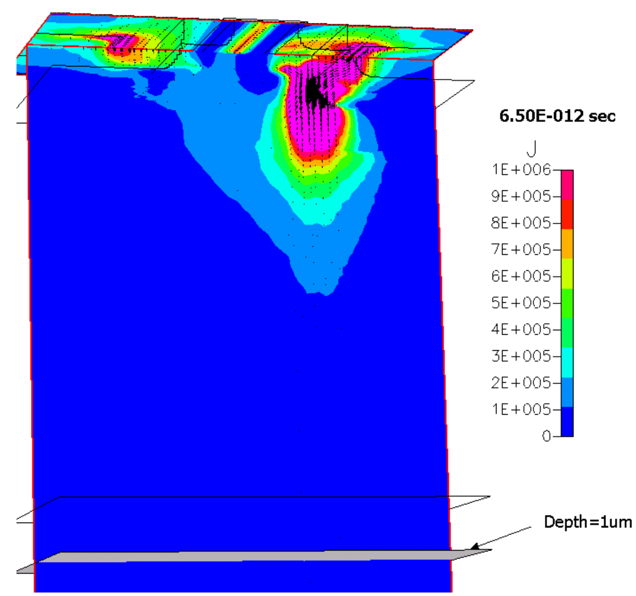




Depth = 1 micron

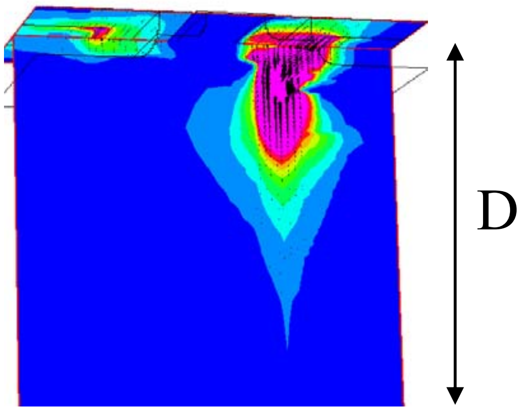
time = 6.5 ps
(Id max)

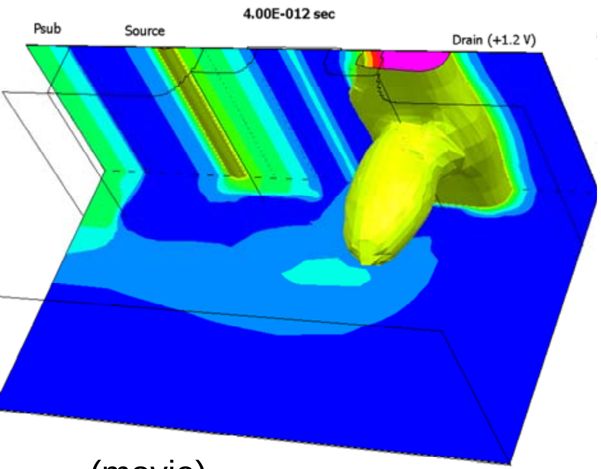




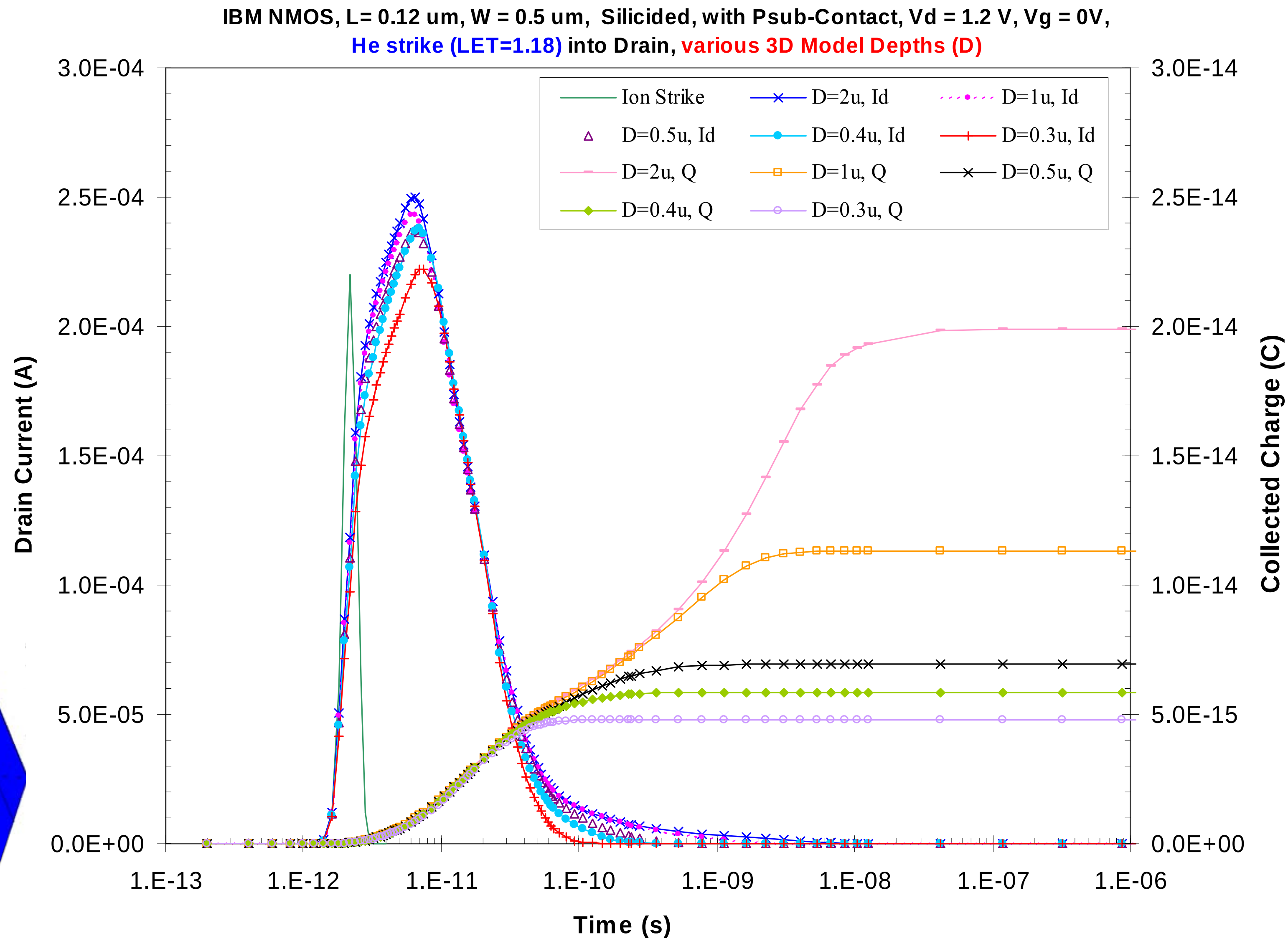
Prompt Charge Collection Depth Analysis

↓ Local Current Density





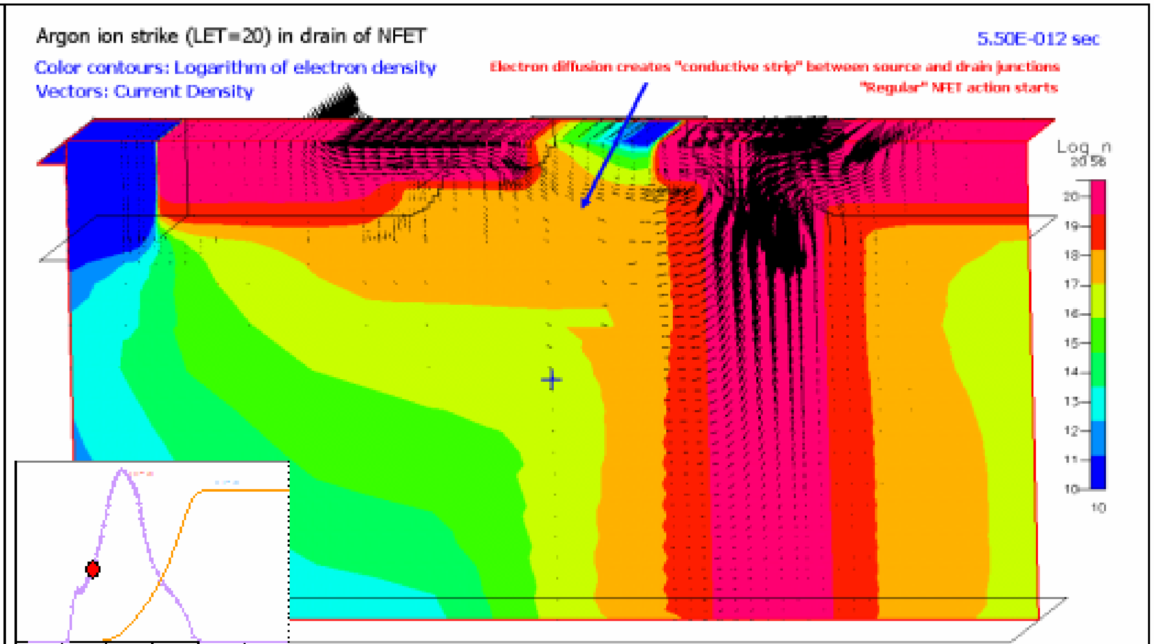
(movie)



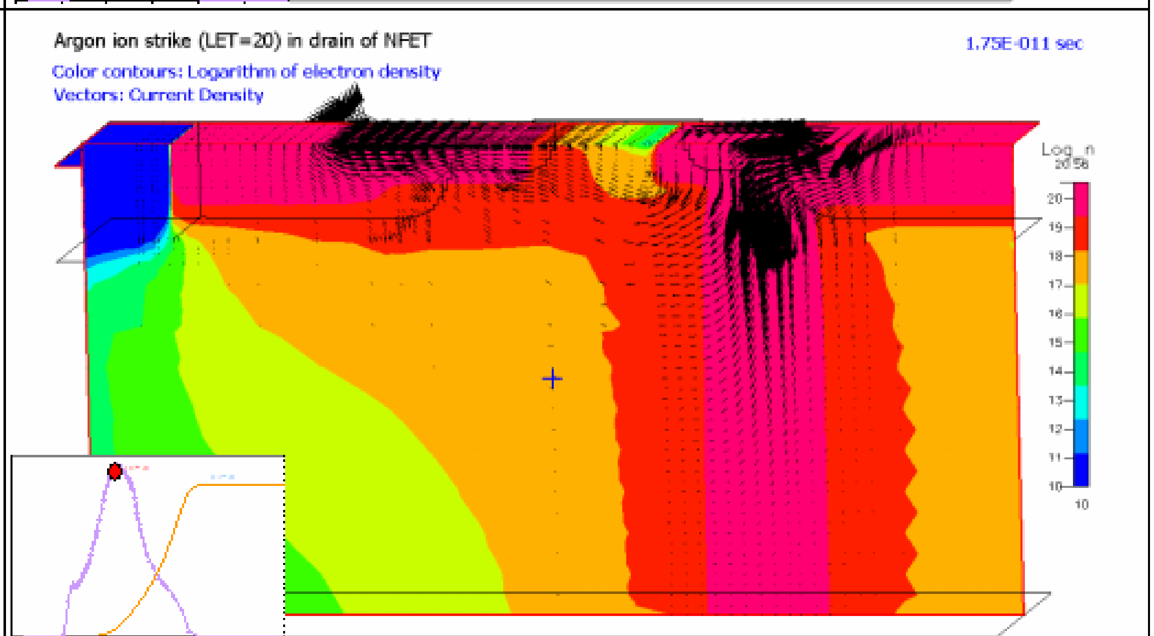
➢ **Prompt Charge Collection Depth ≈ 0.4 μm**

120-nm NFET Drain-Ion-Strike Analysis

Time = 5.5 ps



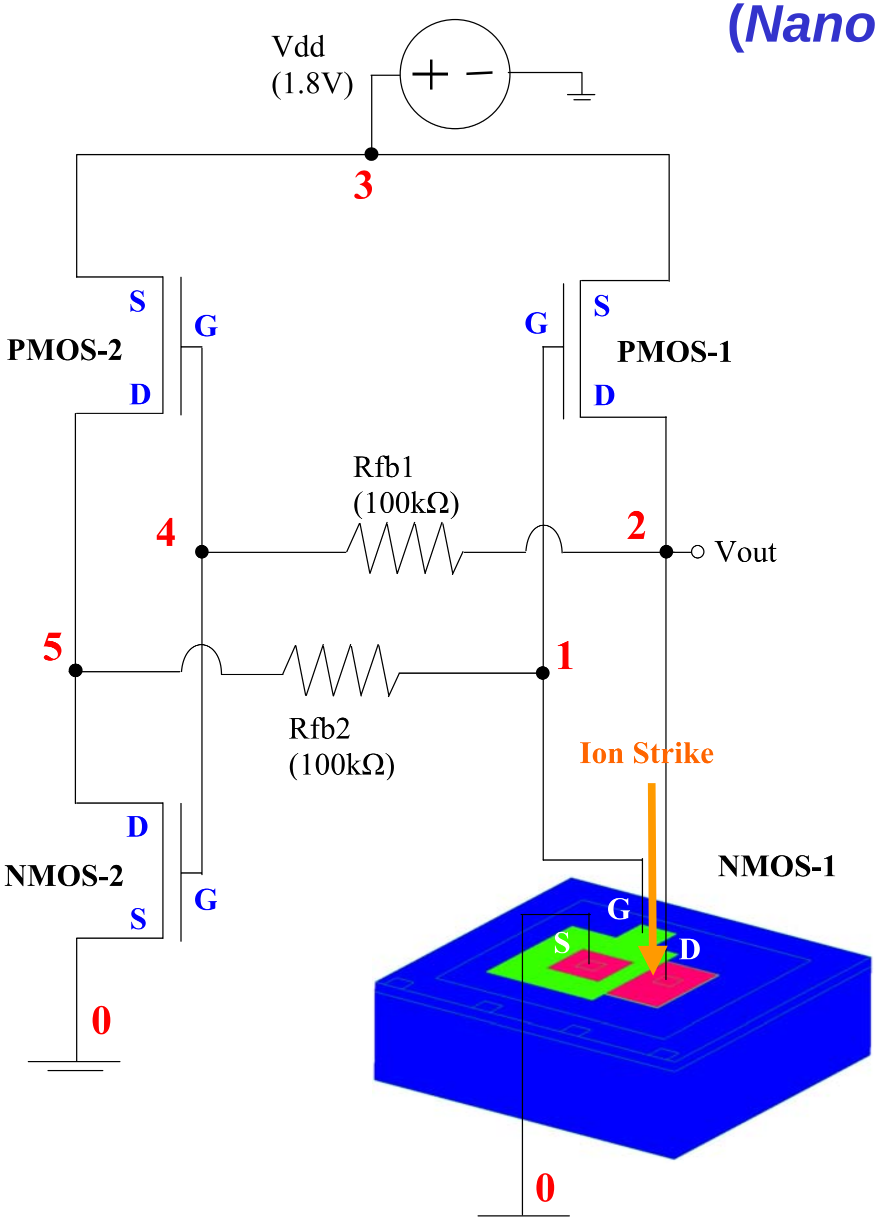
Time = 17.5 ps



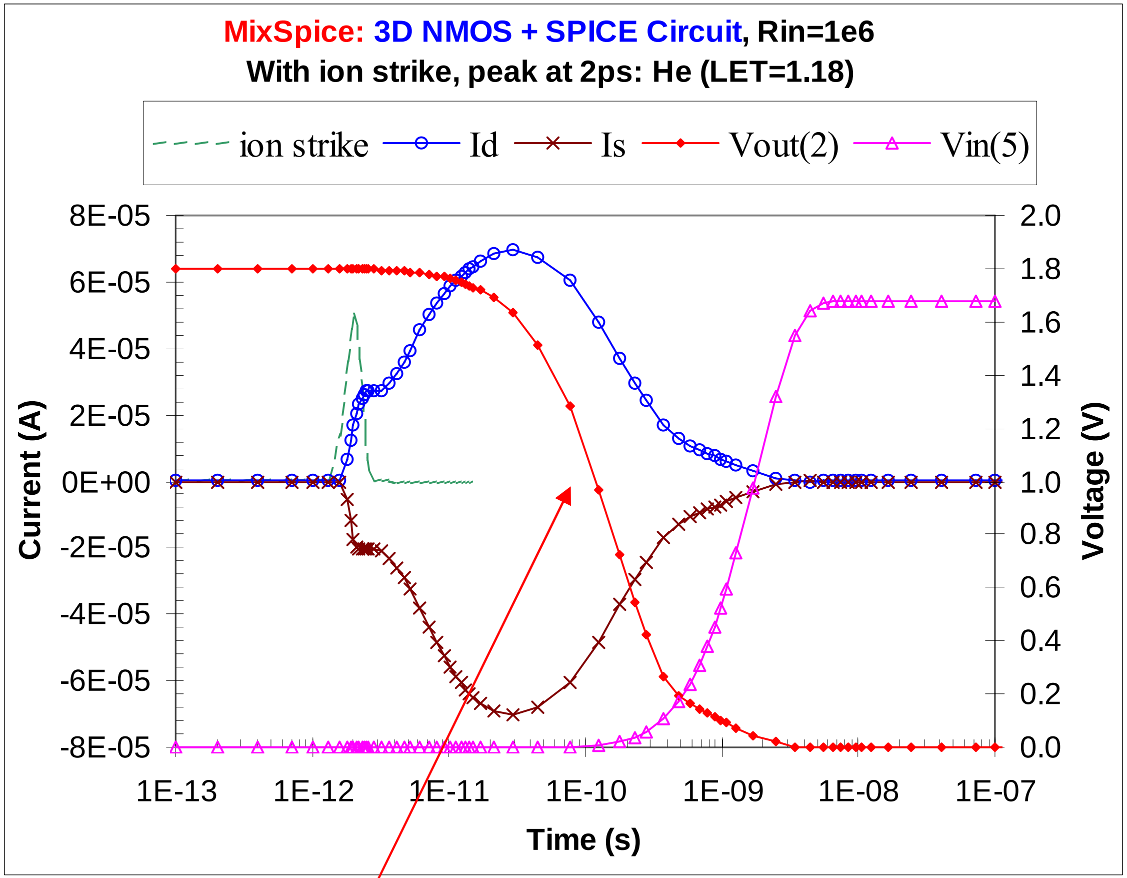
Bipolar action between Source and Drain

Mixed Mode Simulations:
Single-Event Upset (SEU) in SRAM Cell

Mixed-Mode: *SPICE* + 3D Device Model (*NanoTCAD*)



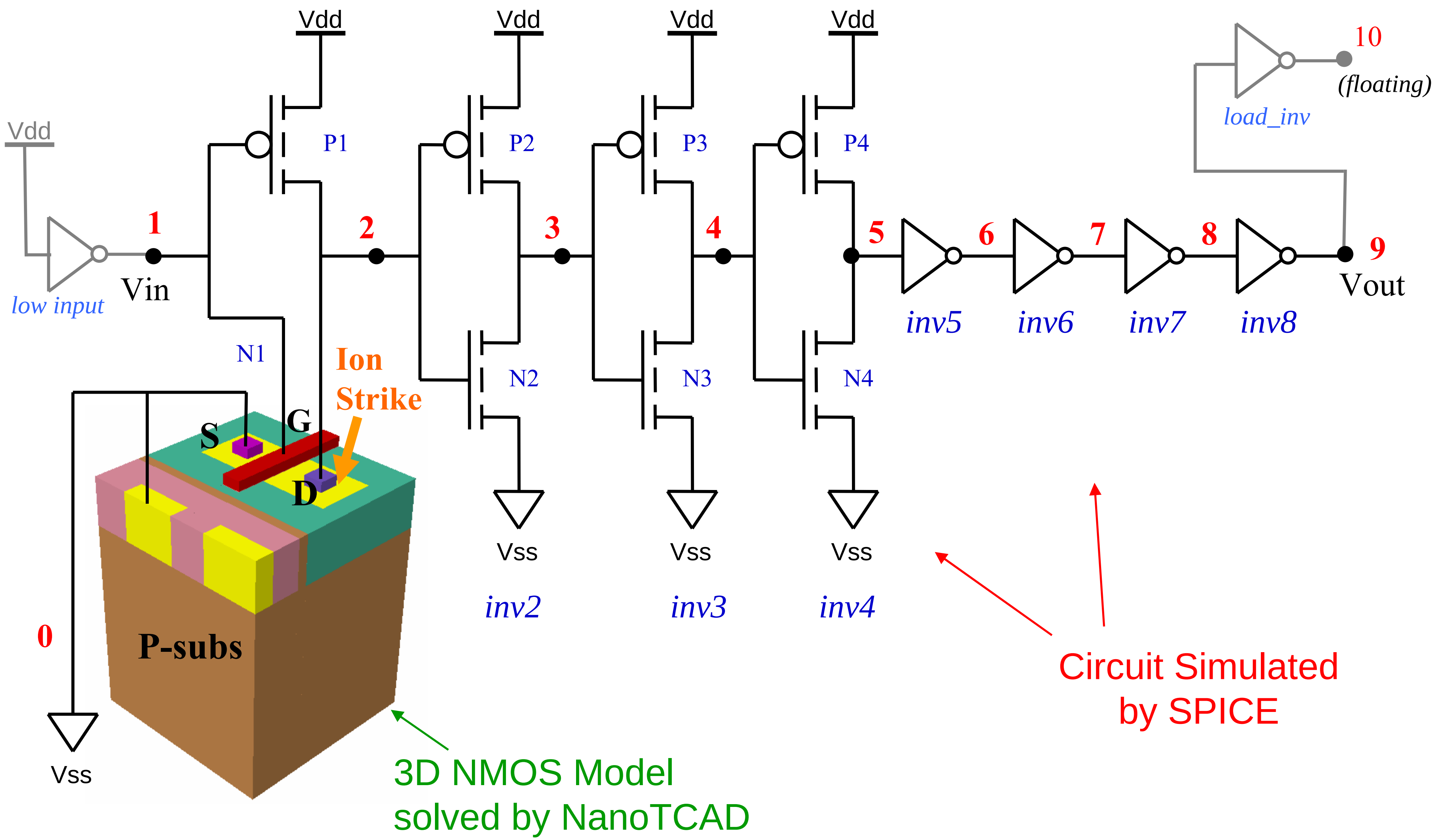
Transient response to heavy-ion strike, calculated by Mixed-Mode in NanoTCAD:



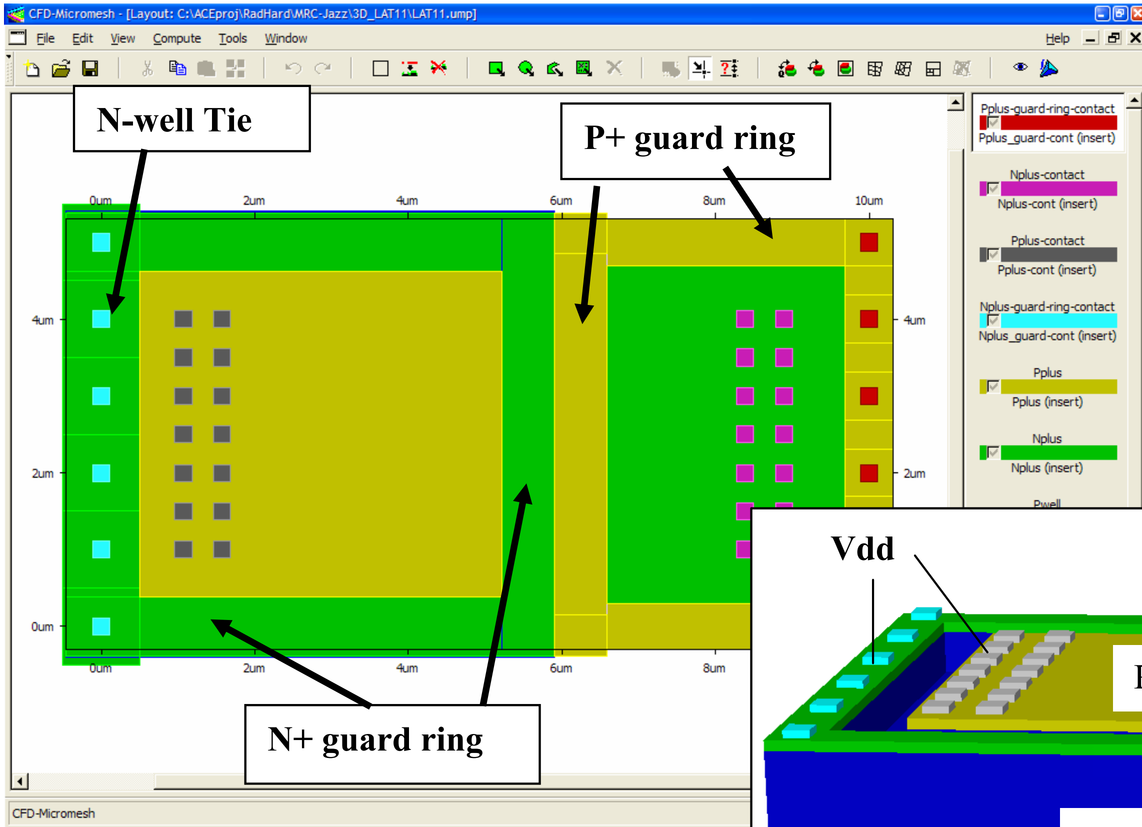
Single-Event Upset (SEU)

SET Pulsewidth Analysis in Logic Circuit

Mixed-Mode Simulation, 0.18-um TSMC technology

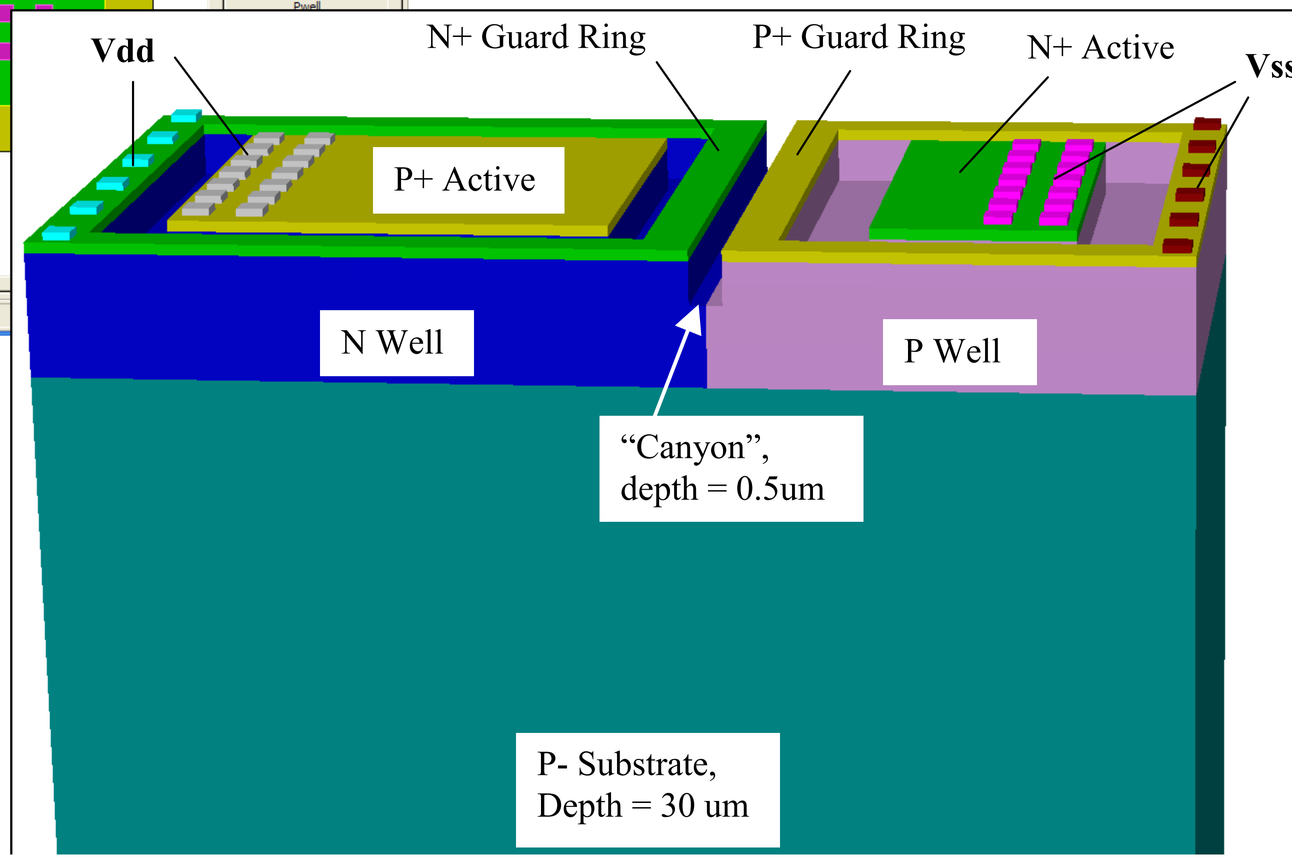


Dose-Rate Simulations of MRC Latchup-Test Cell

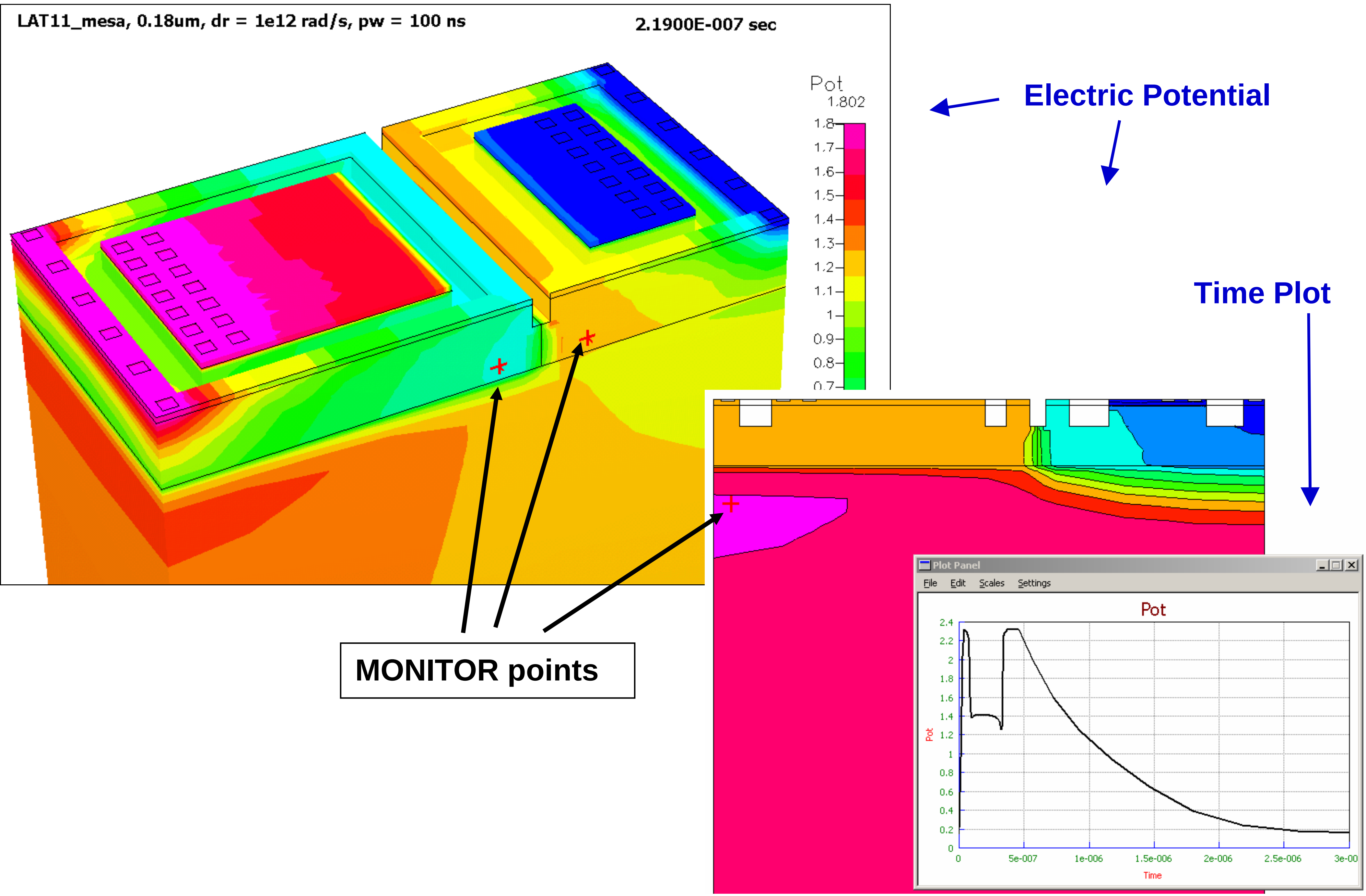


GDSII Layout imported into Micromesh

3D Model



Dose-Rate Effects in MRC Latchup-Test Cell



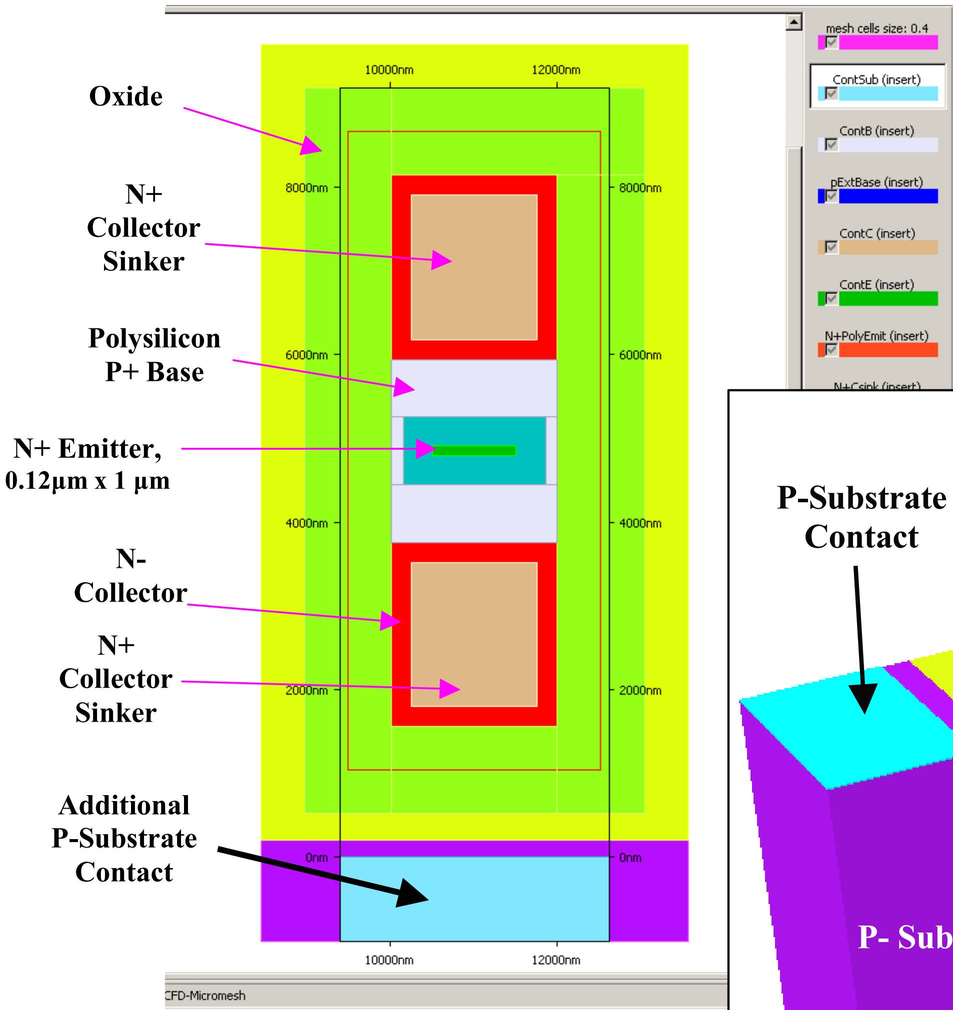
- Analog, Mixed-Signal ICs
- BiCMOS Technologies
- <u>Various Materials</u>

NanoTCAD Modeling of Silicon-Germanium Heterojunction Bipolar Transistors (SiGe HBTs)

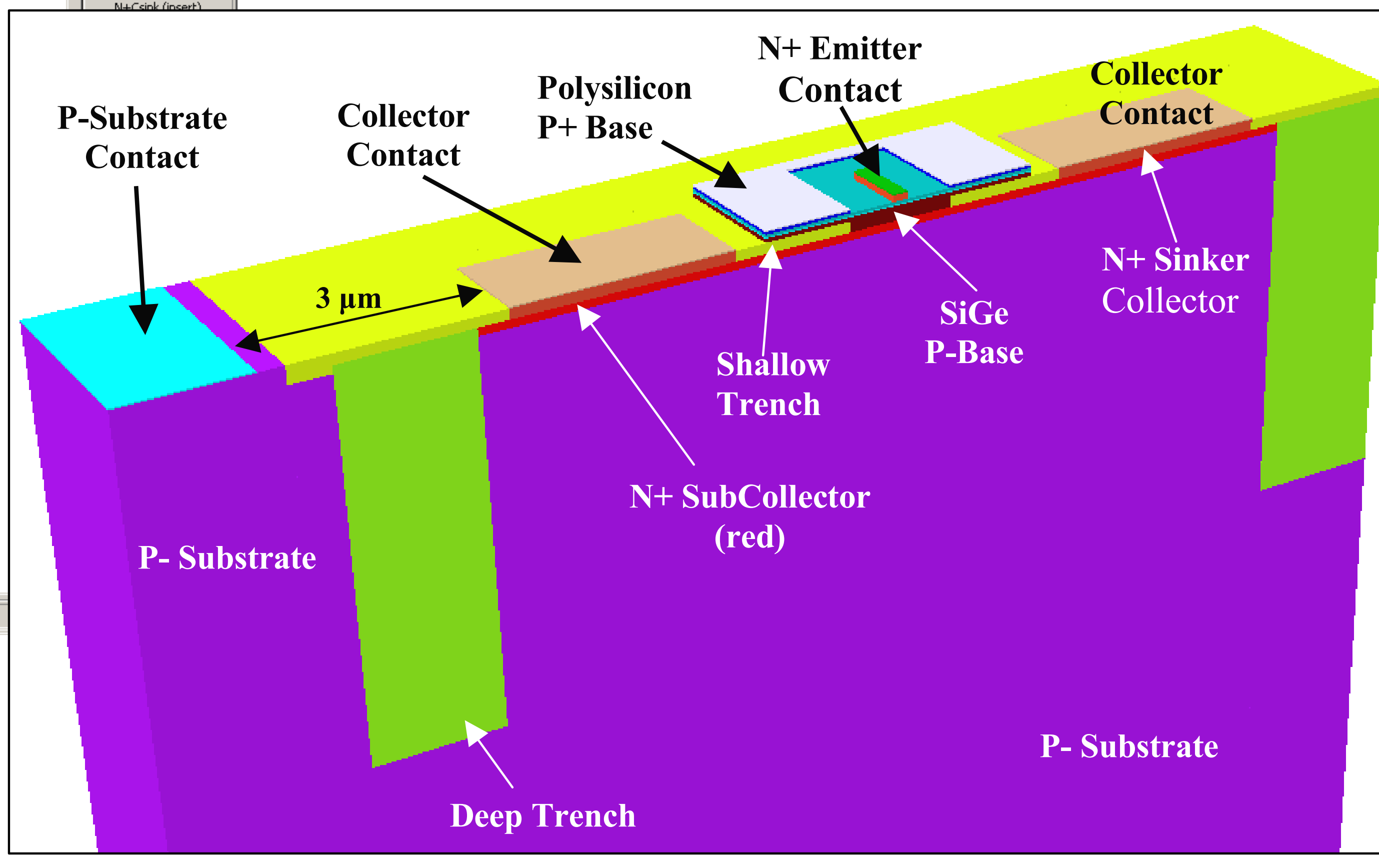
* in collaboration with ATK Mission Research (Anthony Wilson)

CFDRC Model of IBM 130-nm SiGe HBT

Adapted layout from ATK-MR



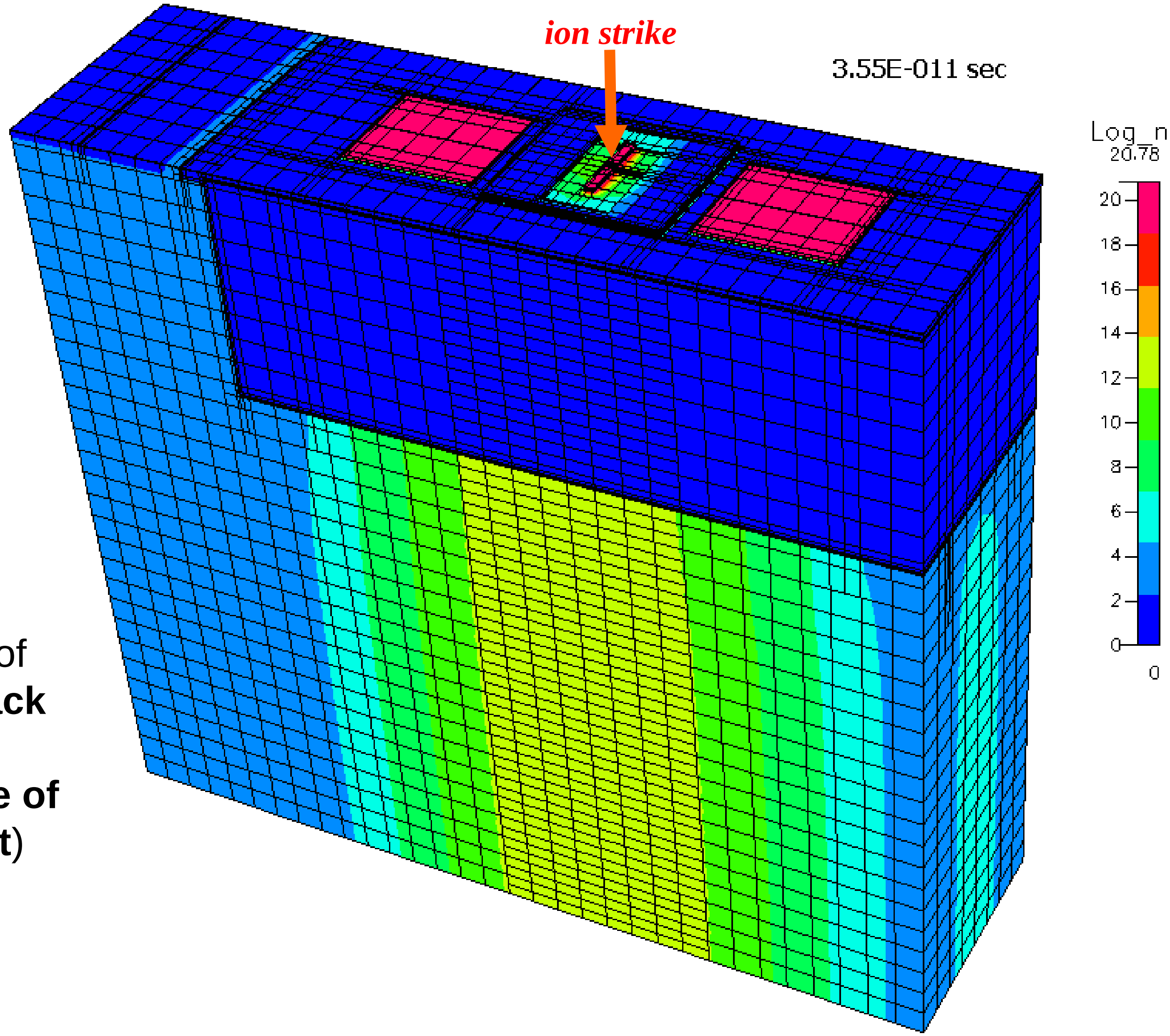
3D Model



3D Simulation of Ion Strike in SiGe HBT

Contact biases:

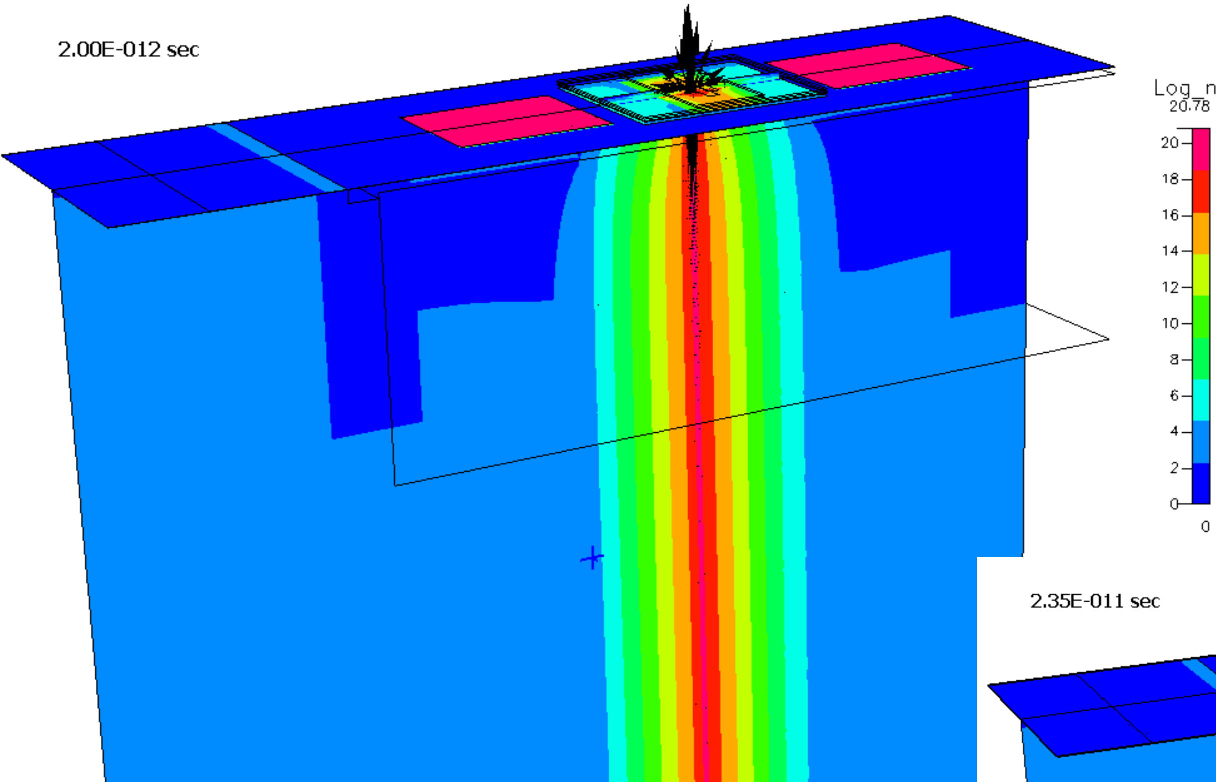
- Vb = 0.3 V
- Vc = 1.2 V
- Ve = 0 V
- Vsub = 0 V



3D mesh is **locally refined** in the area of the modeled **ion track** (passing vertically **through the middle of the Emitter contact**)

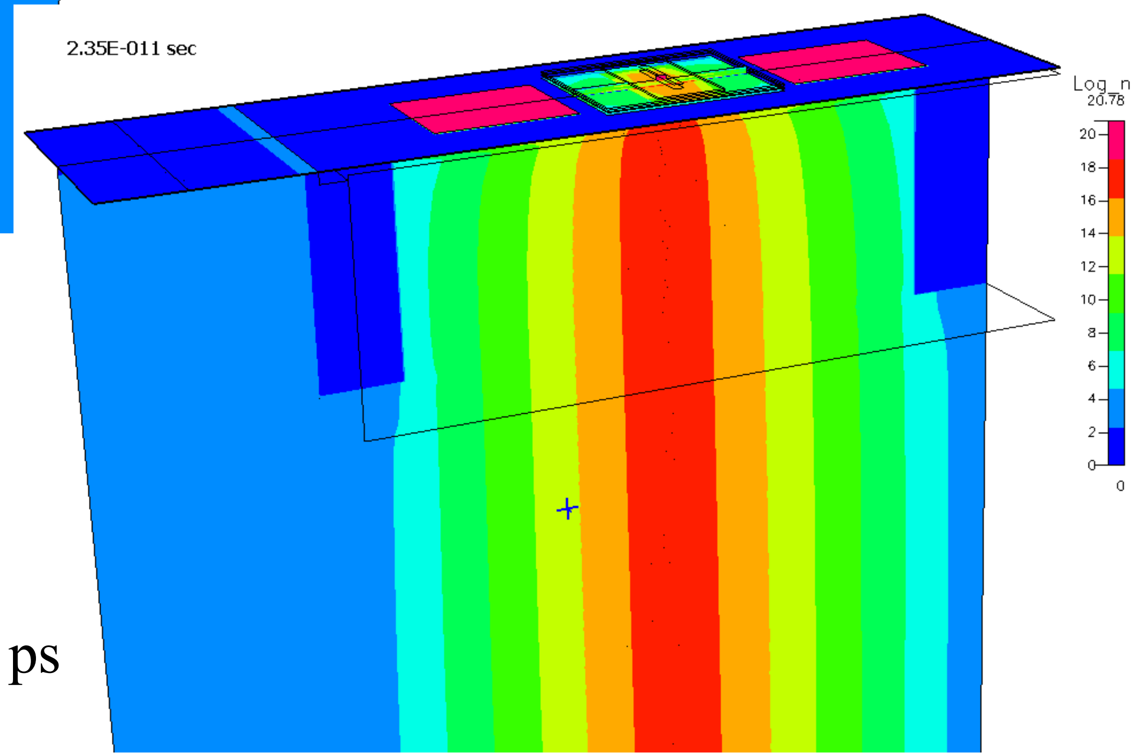
3D Simulation of Ion Strike in SiGe HBT

Local electron density, Log(n)



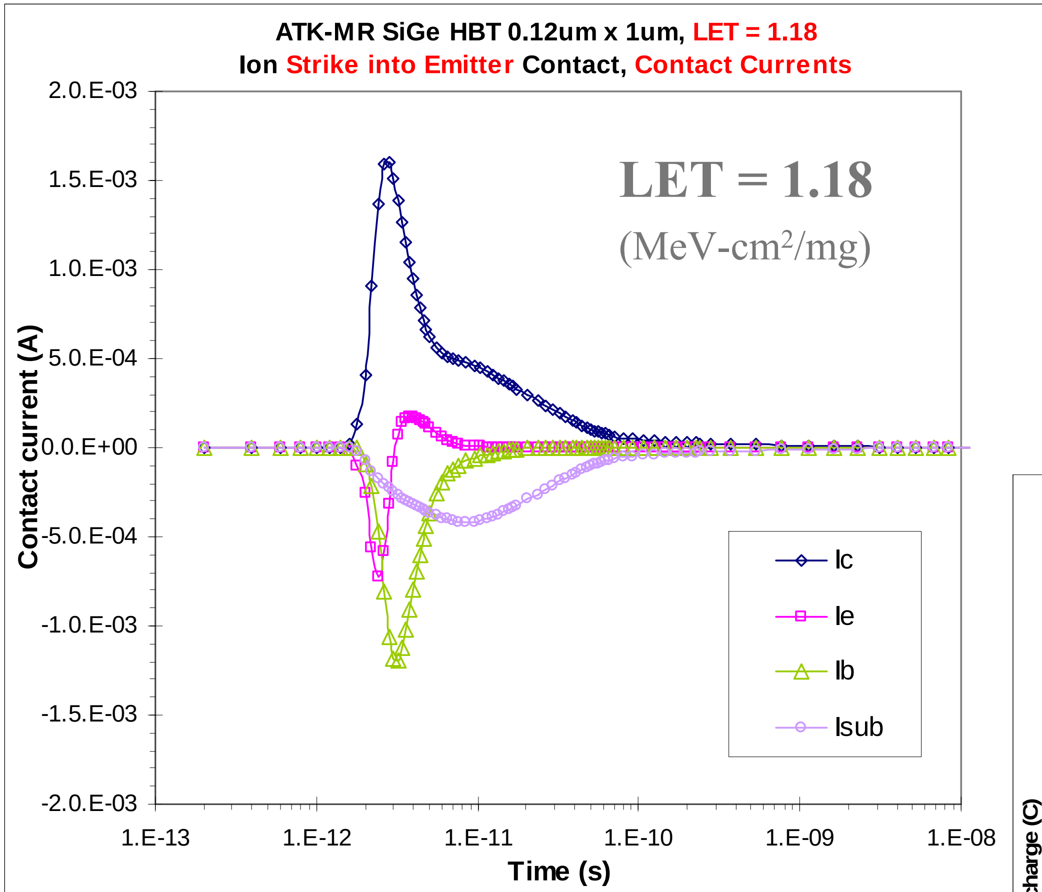
t = 2 ps

ion strike in the middle of Emitter



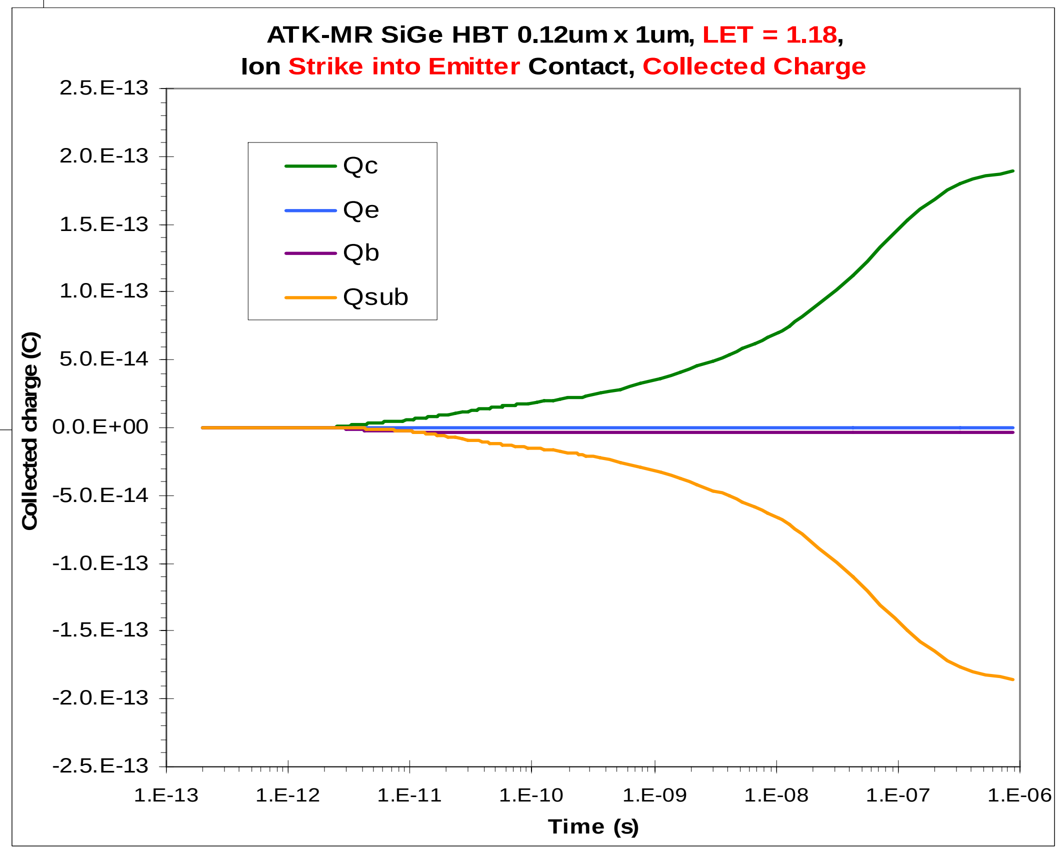
t = 23.5 ps

SE Simulation Results for SiGe HBT



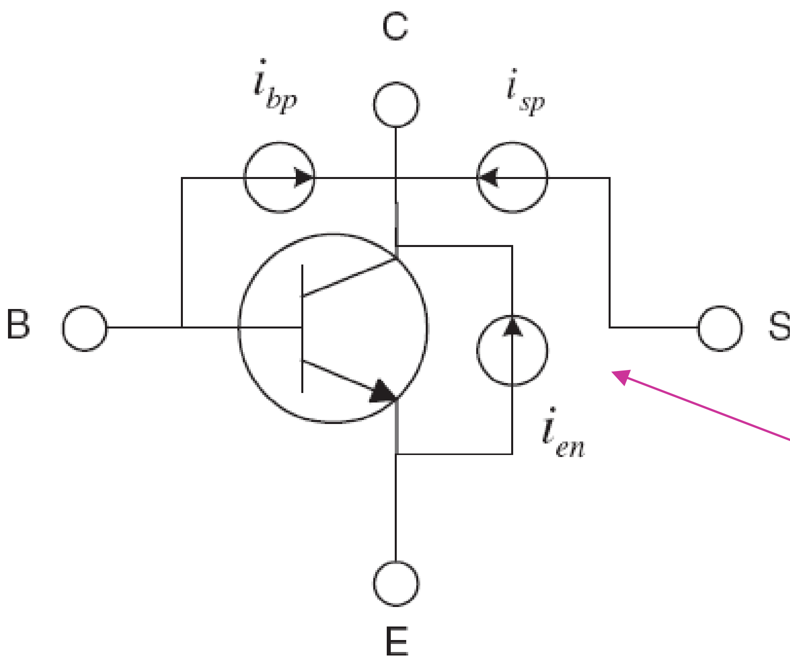
Transient Currents through all the Contacts

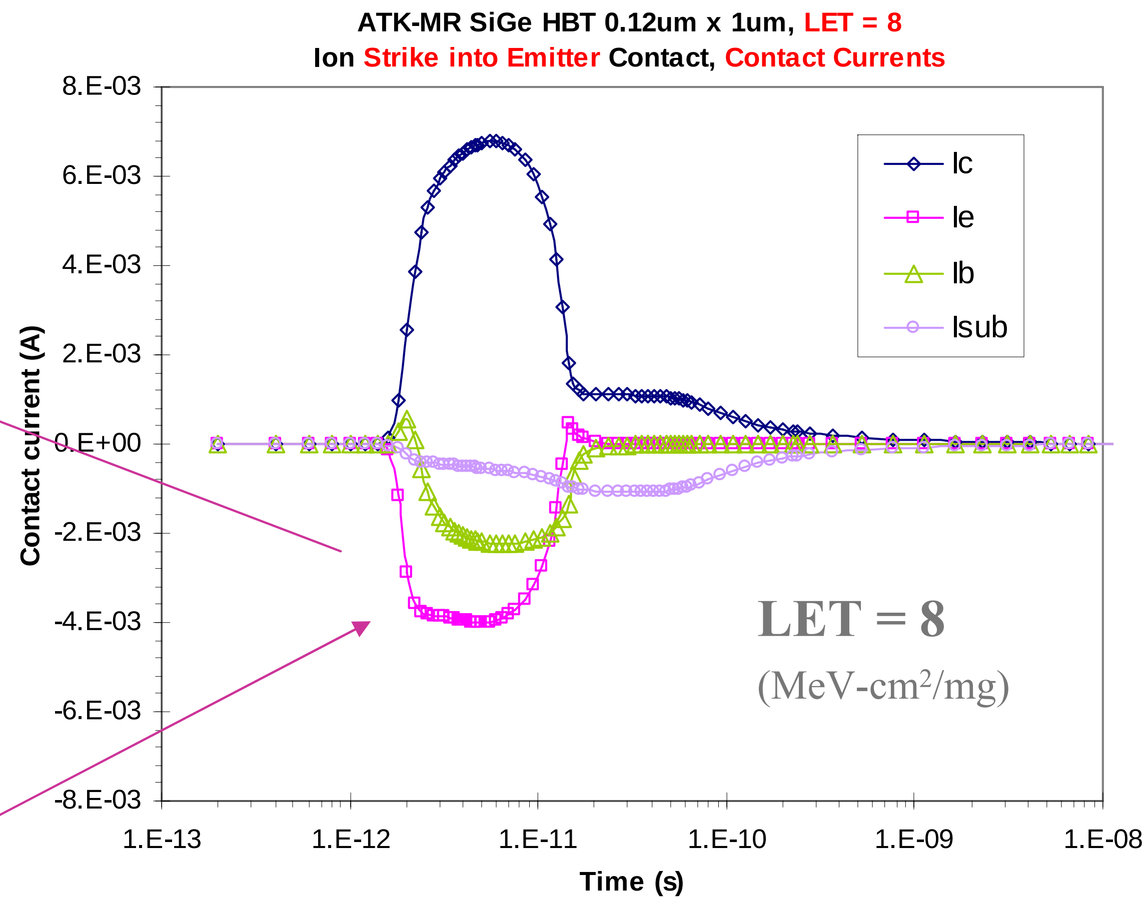
Collected Charge on all the Contacts



SiGe HBT Circuit Model for Single Events

Equivalent circuit model of SEE in HBT for SPICE simulations:





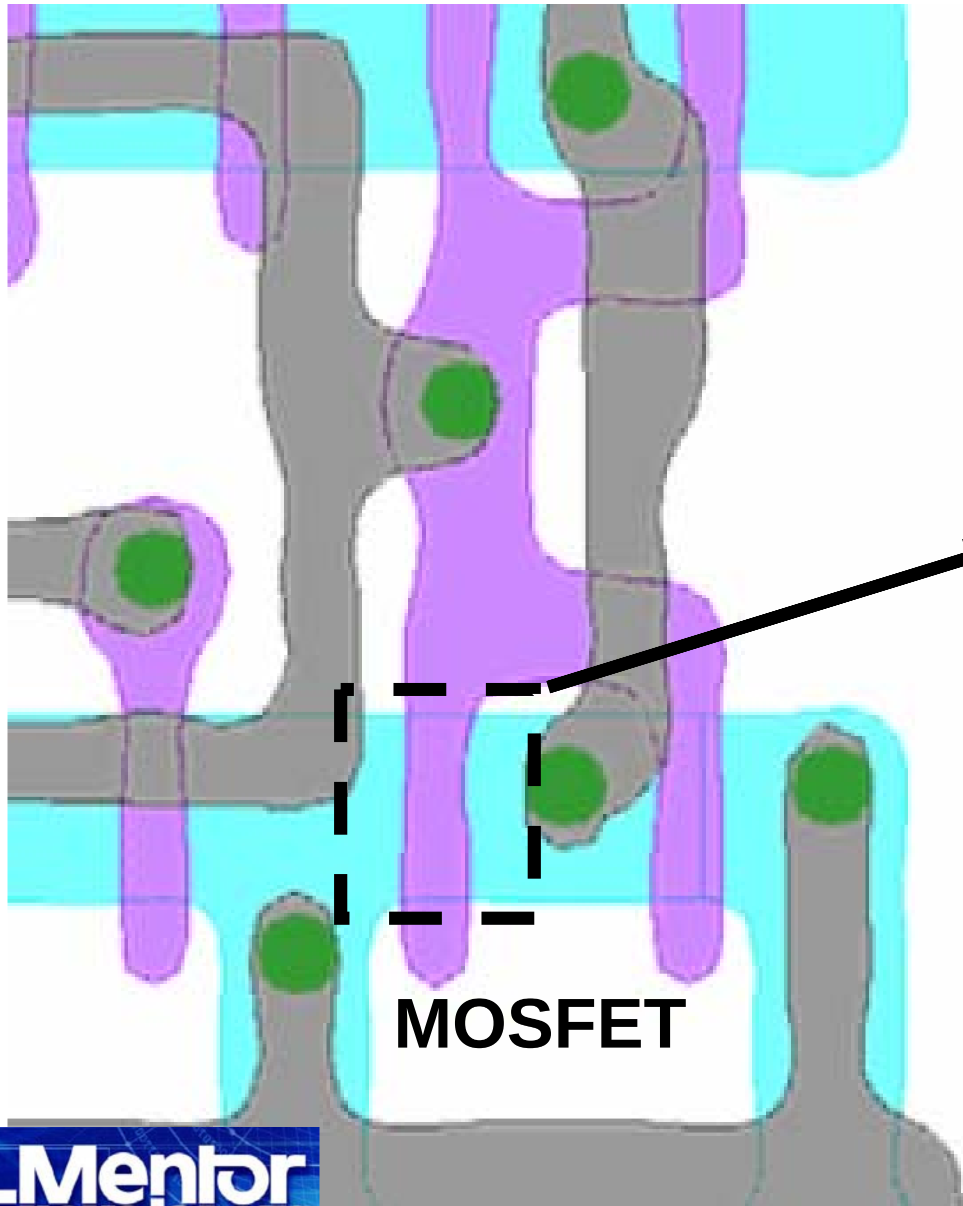
Tabulated results for terminal currents:

Time (s)	Ic (A)	Ie (A)	Ib (A)	Isub (A)
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.00E-13	-1.02E-10	5.27E-13	2.42E-11	7.42E-11
4.00E-13	-1.29E-11	-6.18E-13	6.60E-12	7.24E-12
6.00E-13	-4.47E-12	-9.95E-13	2.66E-12	2.84E-12
8.00E-13	5.16E-11	-5.97E-11	1.77E-11	-9.95E-12
1.00E-12	3.49E-09	-3.79E-09	1.05E-09	-7.68E-10
1.20E-12	1.20E-07	-1.28E-07	3.32E-08	-2.64E-08
1.40E-12	2.23E-06	-2.27E-06	5.11E-07	-4.85E-07
1.60E-12	2.27E-05	-2.11E-05	3.03E-06	-4.73E-06
1.80E-12	1.29E-04	-1.02E-04	-2.81E-06	-2.46E-05

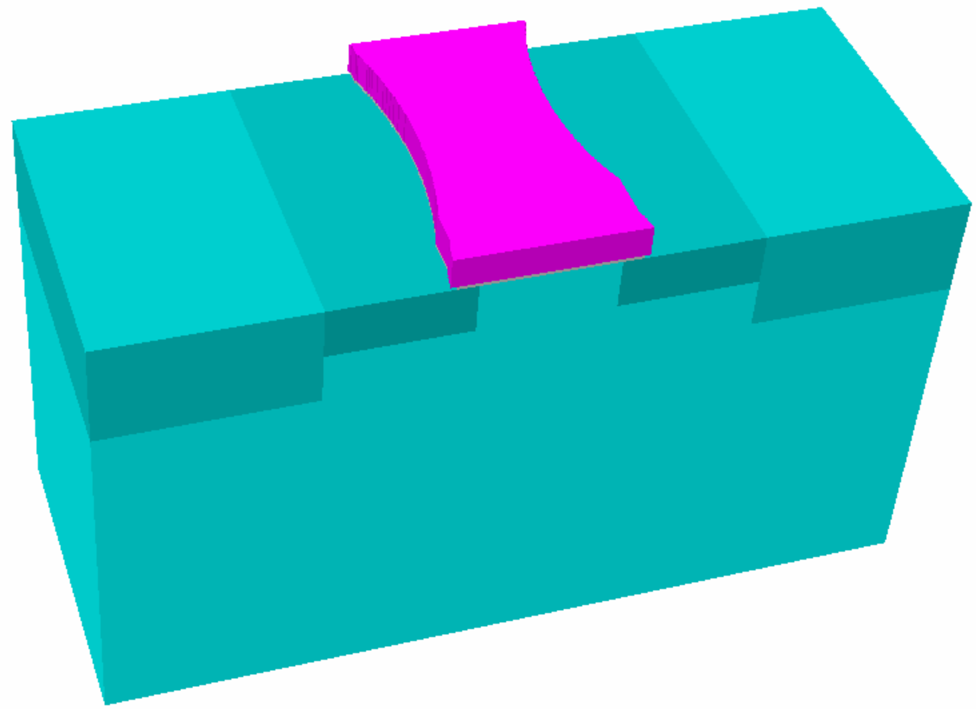
3D TCAD Simulations
provide SE data for PWL SPICE models

Nanoscale IC Layouts Distorted by Subwavelength Lithography (OPC)

90-nm CMOS Layout with RET



… need 3D TCAD Models
with accurate geometry



OPC = Optical and Process Correction
RET = Resolution Enhancement Technology

CFDRC NanoTCAD Customers

NanoTCAD has been used for Radiation-Effects Analysis and Radiation-Hardened Designs by

- **Mission Research Corporation (now ATK-MR)**
  (Michael Mostrom, David Mavis, Anthony Wilson, Keith Avery)
- **Honeywell**
  (Jerry Yue, Dave Fulkerson)
- **Northrop Grumman**
  (Michael Fitzpatrick, Alfred Turley)
- **US Navy - NAVSEA Crane**
  (Mark Savage)
- **US Air Force - AFRL, Space Vehicles Directorate, Kirtland AFB**
  (David Alexander)

Dr. Michael Mostrom, ATK Mission Research: ***"The three-dimensional simulations of radiation effects in semiconductor devices helped us significantly to better understand underlying phenomena, and then develop new concepts and behavioral models of our radiation-hardened devices and circuits. I was pleased with the technical competence and equally high level of responsiveness provided by CFDRC's staff"***

Joint STTR of CFDRC and Vanderbilt / ISDE

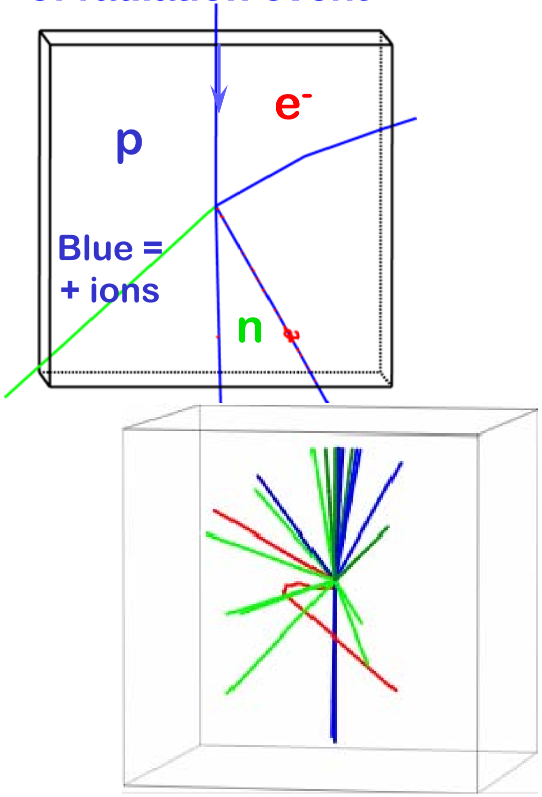
STTR Phase I Project, sponsored by **NASA** Ames (2005-06)

Program Objectives:

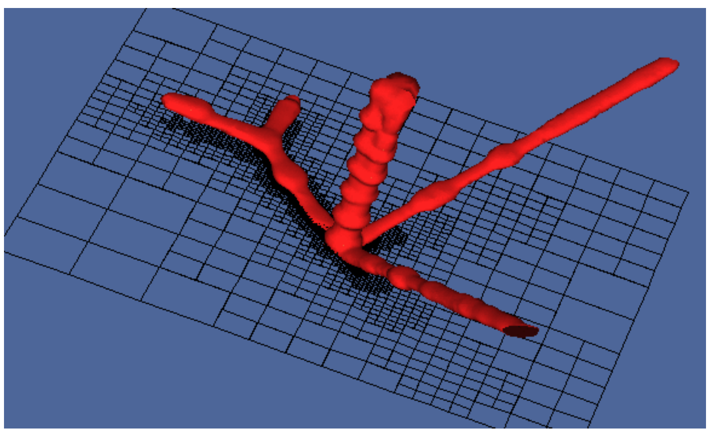
- **Couple** Vanderbilt **Geant4 and** CFDRC **NanoTCAD 3D Device Solver**
- **Adaptive/dynamic 3D meshing** for multiple ion tracks
- **Statistically meaningful** runs on a **massively parallel computing cluster**
- **Integrated and automated** interface of **Geant4** and **CFDRC NanoTCAD**

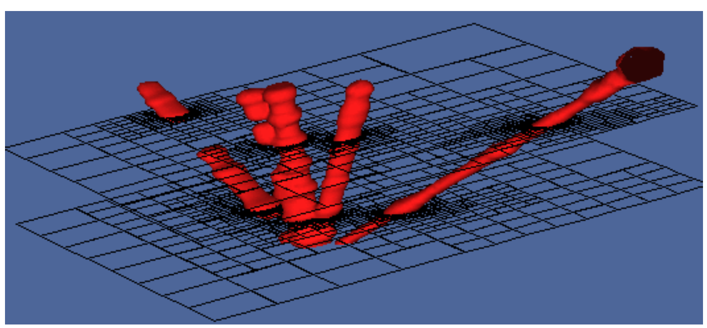
Geant4

- accurate model of radiation event

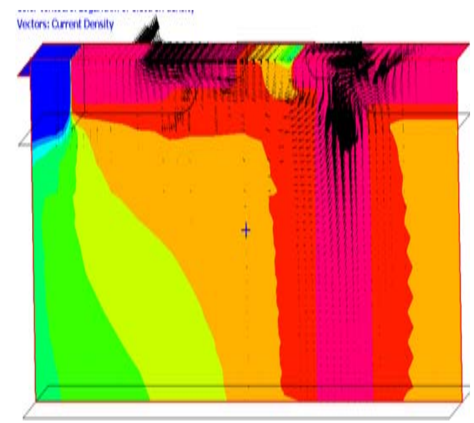


- Adaptive 3D meshing of tracks

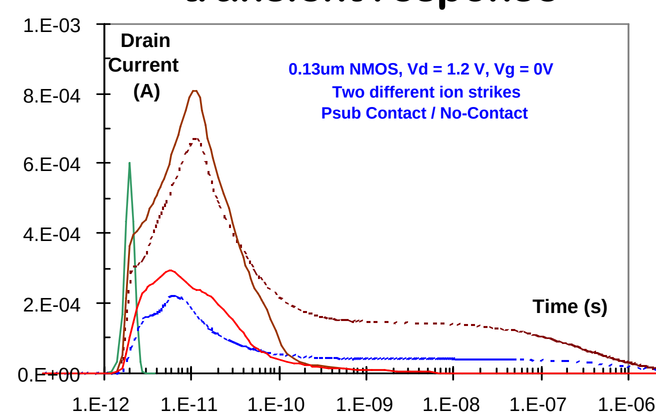




- 3D Nanoscale transport



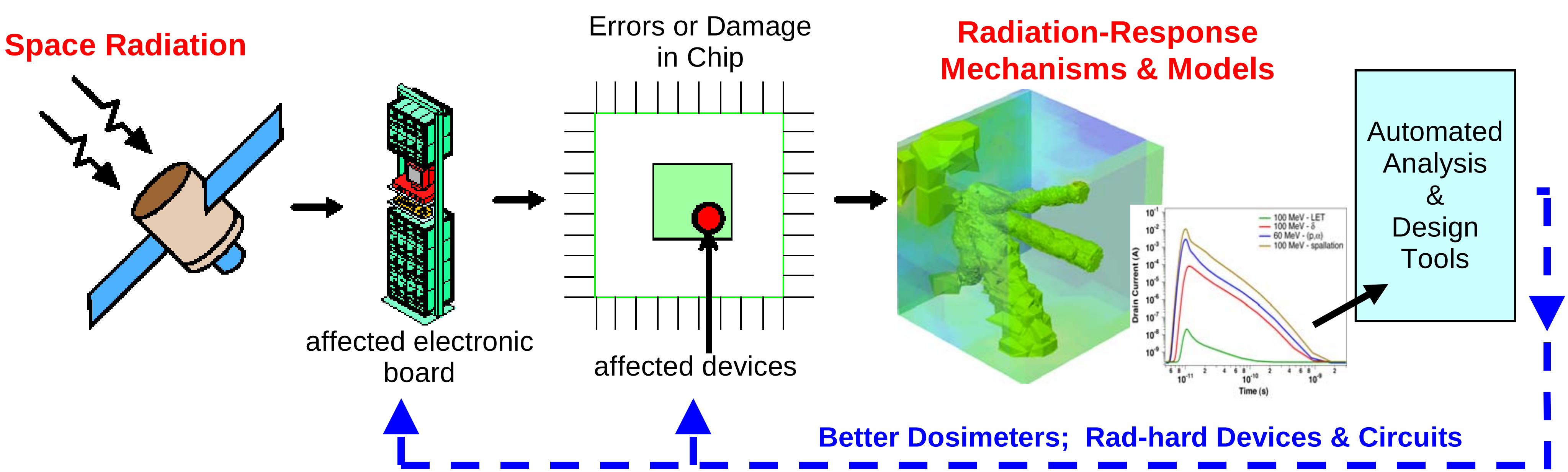
- Physics based transient response



Significance for Space / Defense Electronics

The **new, more accurate radiation-effects models**, which better reflect the true deep-space environment of exploration missions, will lead to development of **new tools that will help NASA to:**

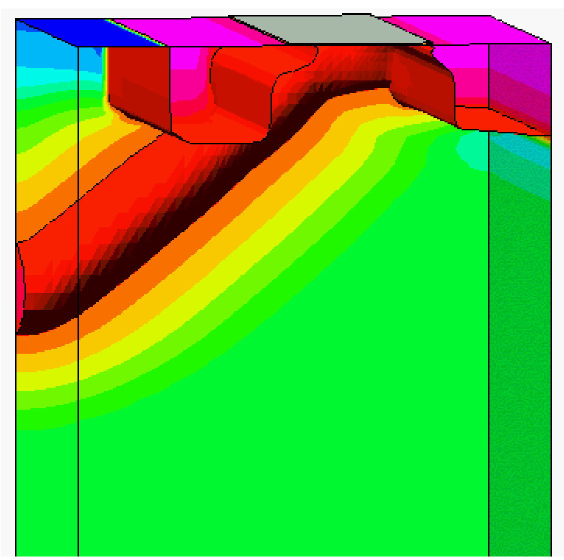
- **better understand and predict response** of nano-devices and novel materials **to space radiation environment**, particularly high atomic number and energy particles (HZE particles) and energetic protons (**not available at ground testing**);
- **assess technologies, devices, and materials** of new electronic systems;
- better evaluate the radiation response **at early design stage**;
- develop and assess **radiation hardening techniques** for exploration electronics;
- **reduce the amount of testing cost and time**.



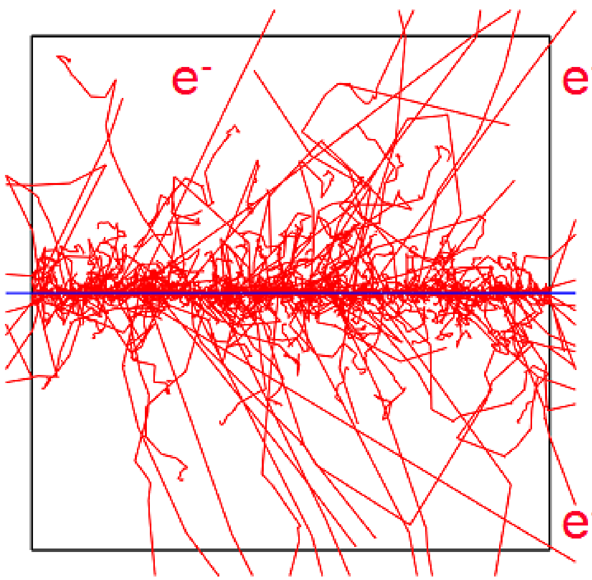
Myth of the Average Event

Vanderbilt University has recently developed a **unique capability**, enhancing and applying **Geant4** libraries to the **detailed simulation of radiation events in nano-scale** device structures [*HEART 2004, NSREC 2004, NSREC 2005, IEEE Tr. NS 2005*]

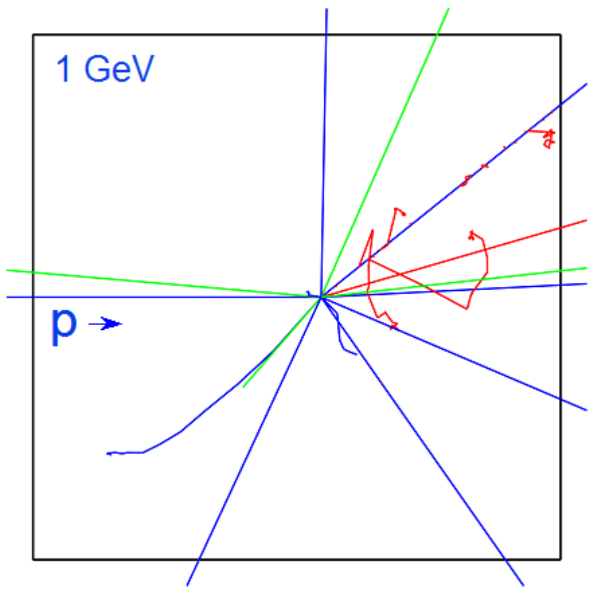
- Energy deposition by ionizing particles (so called single event effects) can no longer be treated as an average deposition (linear energy transfer, LET) along a linear path
- More accurate: ensembles of events, with **multiple secondary events and unique complex micro-structures**, recently computed using the new Vanderbilt Geant4 tools



Ion-strike **LET-based model** (**CFDRC** simulation, 2001)

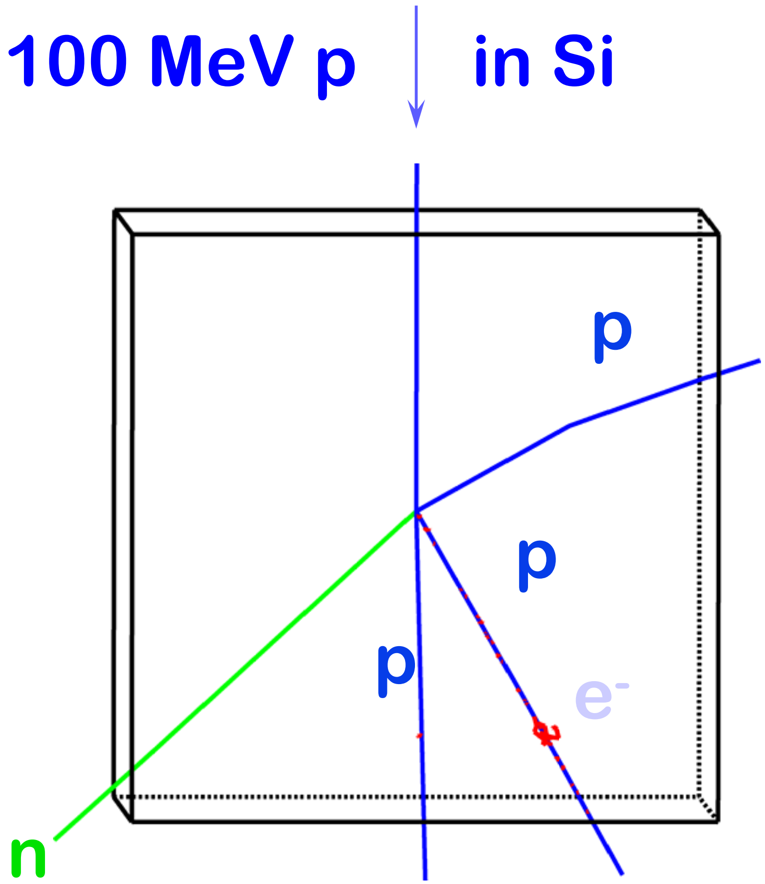


100 MeV proton ⇨ Si, $\Delta E \approx 1$ keV (**Vanderbilt Geant4** simul., 2004)



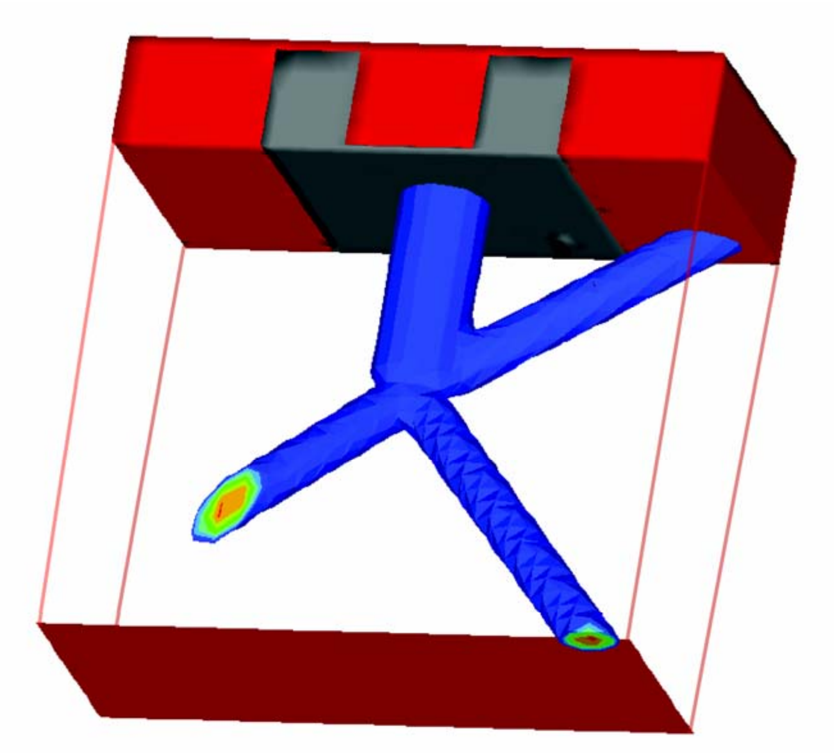
1 GeV proton, Deposited: 148 keV (**Vanderbilt Geant4** simul., 2004)

Simulation: A Radiation Event with Microstructure



A spallation event: Geant4

MOS Transistor

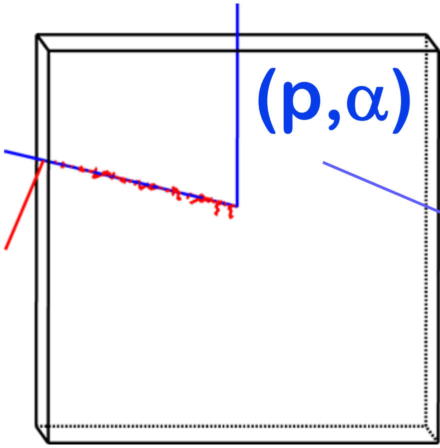


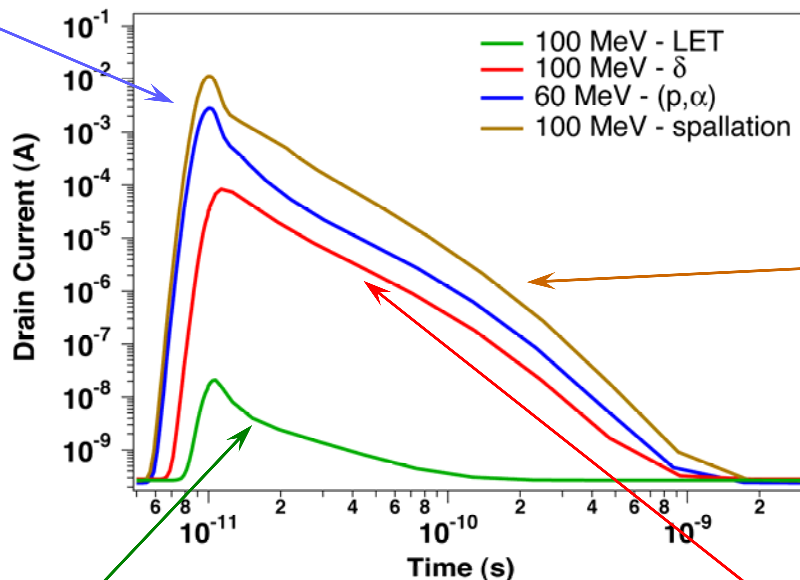
3D device simulation

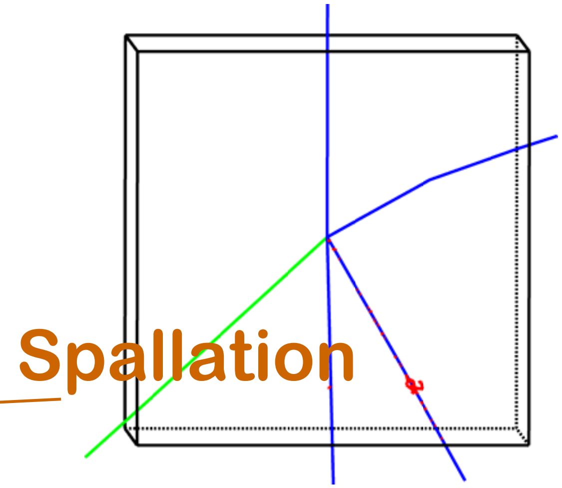
MOS Transistor Response

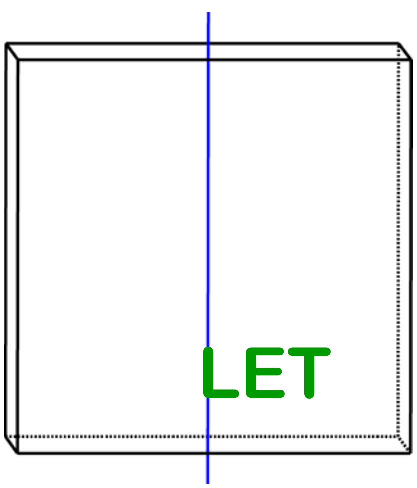
Vanderbilt University

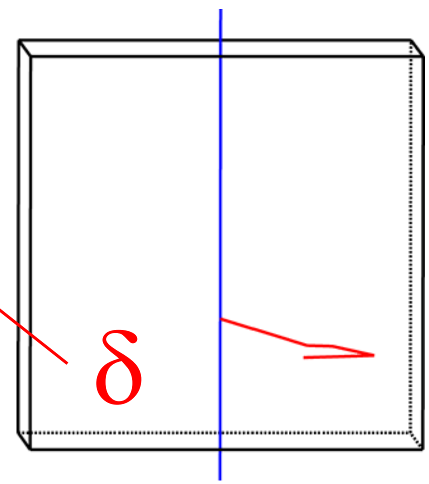
Drain current versus time for various events











The new, more accurate models give results significantly different than the standard LET model.

Conclusions from the Recent Studies of VU

- LET, an average quantity, does not characterize the range of extreme events.
- Deposited energy and charge have complex microstructure that is relevant to device response.
- Submicron device response is strongly dependent on the microstructure of the radiation event.
- Future single event simulation will require both detailed radiation event simulations and coupled device response computations.

[R. A. Weller, A. L. Sternberg, A. S. Kobayashi, L. W. Massengill, R. D. Schrimpf, and D. M. Fleetwood, "Modeling Semiconductor Device Response using Detailed Radiation Event Simulations," *HEART 2004* Conf.]

A New, Adaptive Mesh Generator from CFDRC for Accurate Capturing of *Geant4* Event Tracks

Vanderbilt University

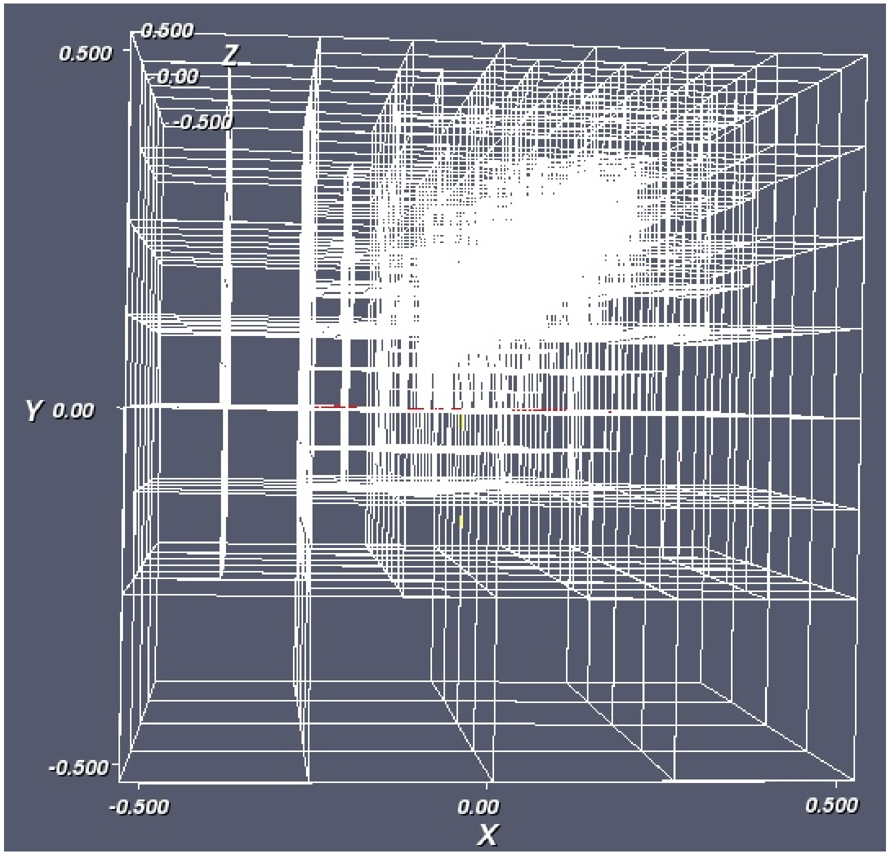
Different applications (like NanoTCAD and Geant4) require **different mesh cell types:**

- **hexahedral** cells are preferable for **NanoTCAD** to ensure high accuracy of simulations,
- **tetrahedral** cells are preferable for **Geant4** interfaces, to enable a faster ion tracking in 3D geometry.

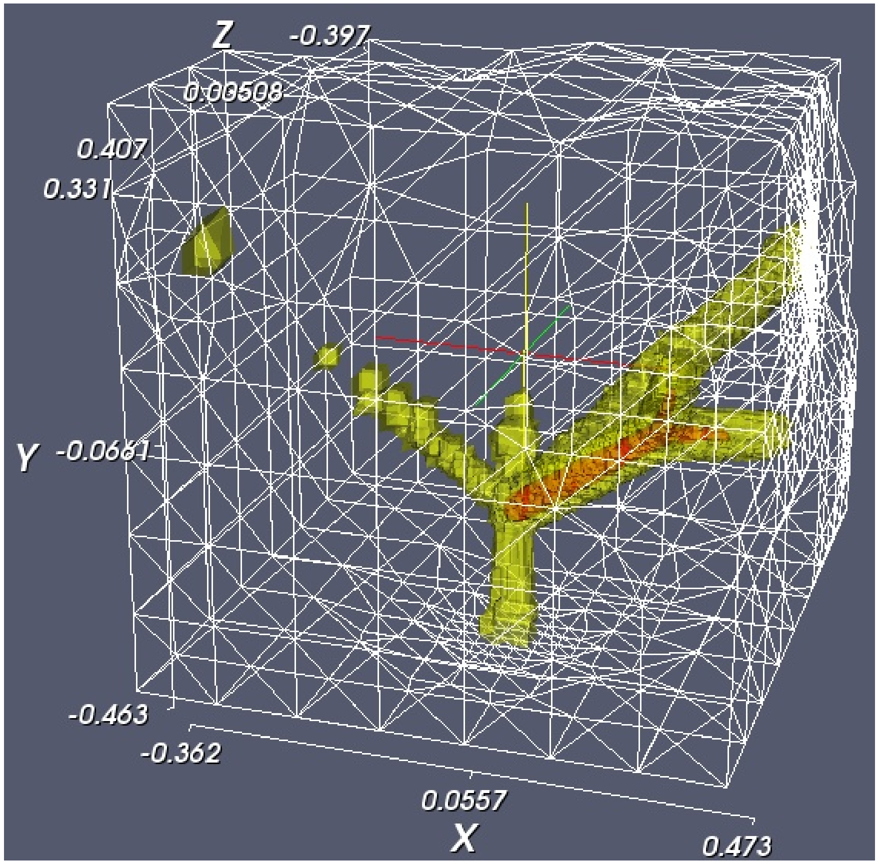
Such a dynamic, adaptive 3D mesh generation is currently not available commercially - hence, it is an ***innovative tool***.

CFDRC developed new 3D adaptive mesh generation tool, named ***Germes*** (for Gerris-based mesher)

hexahedra



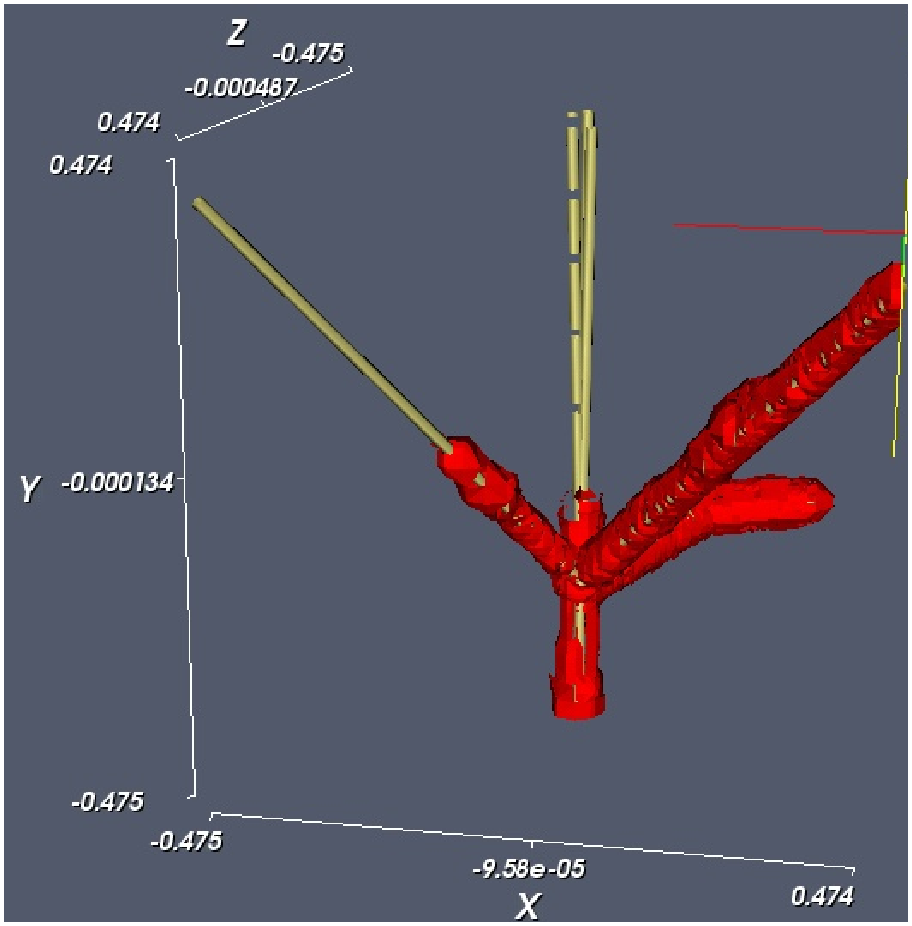
tetrahedra



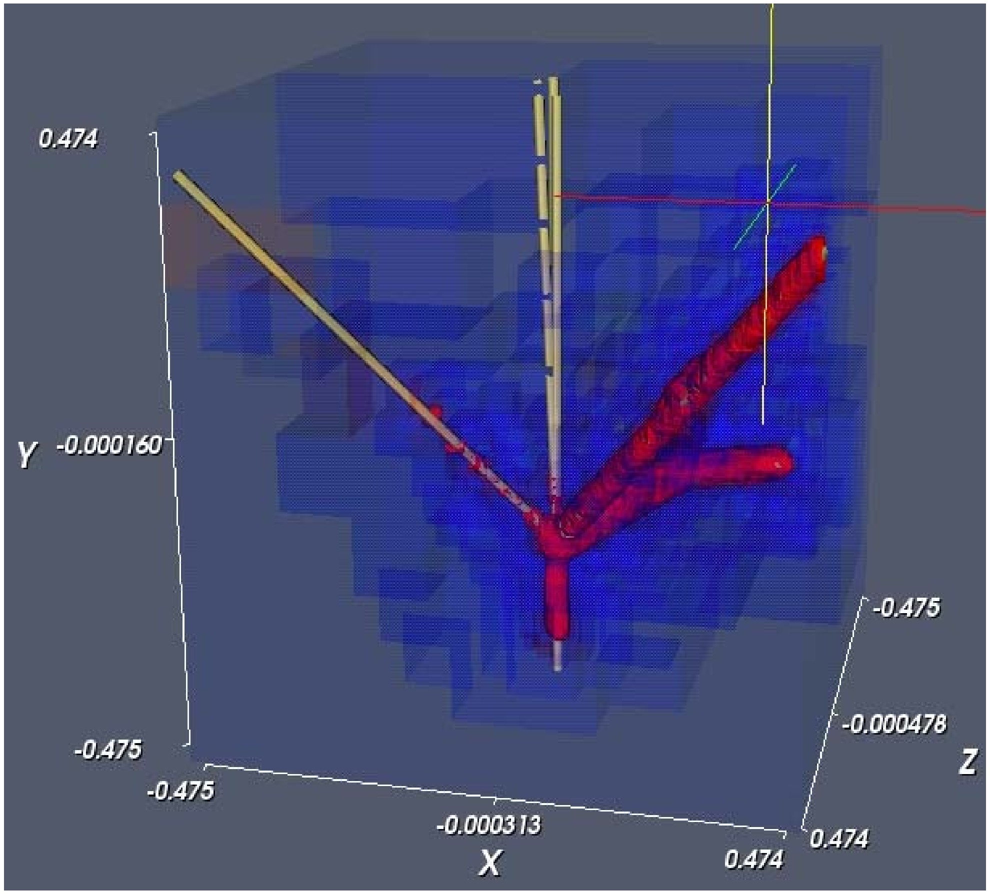
New *ParaView* interface for Geant4 Tracks, Energies, and 3D Mesh Visualization

In Phase 1, CFDRC developed new interfaces for *Vanderbilt-Geant4* tools to the *ParaView* code (free, open-source), for visualization of Geant4 track structures, energy depositions, and adaptive 3D meshes.

Geant4-generated track structure (yellow) + isosurface of a deposited energy level (red)



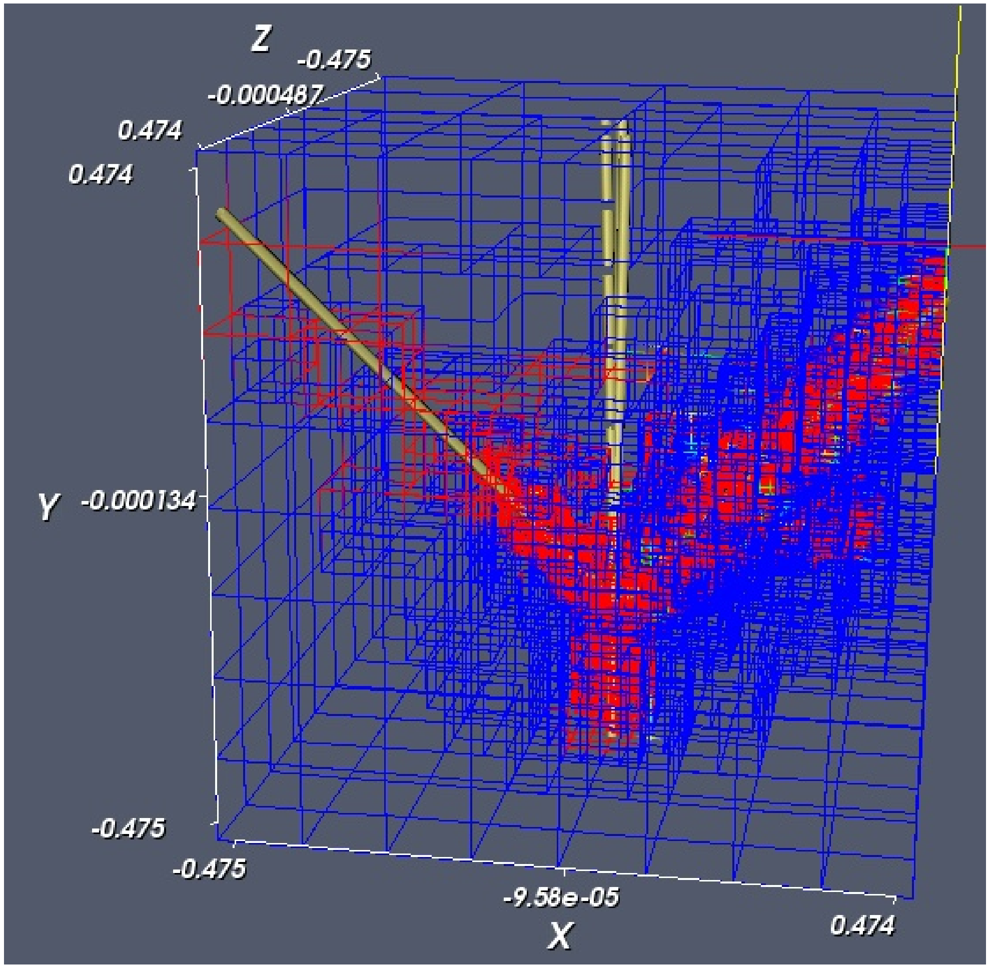
… plus hexahedral 3D meshing view (semi-transparent blue)



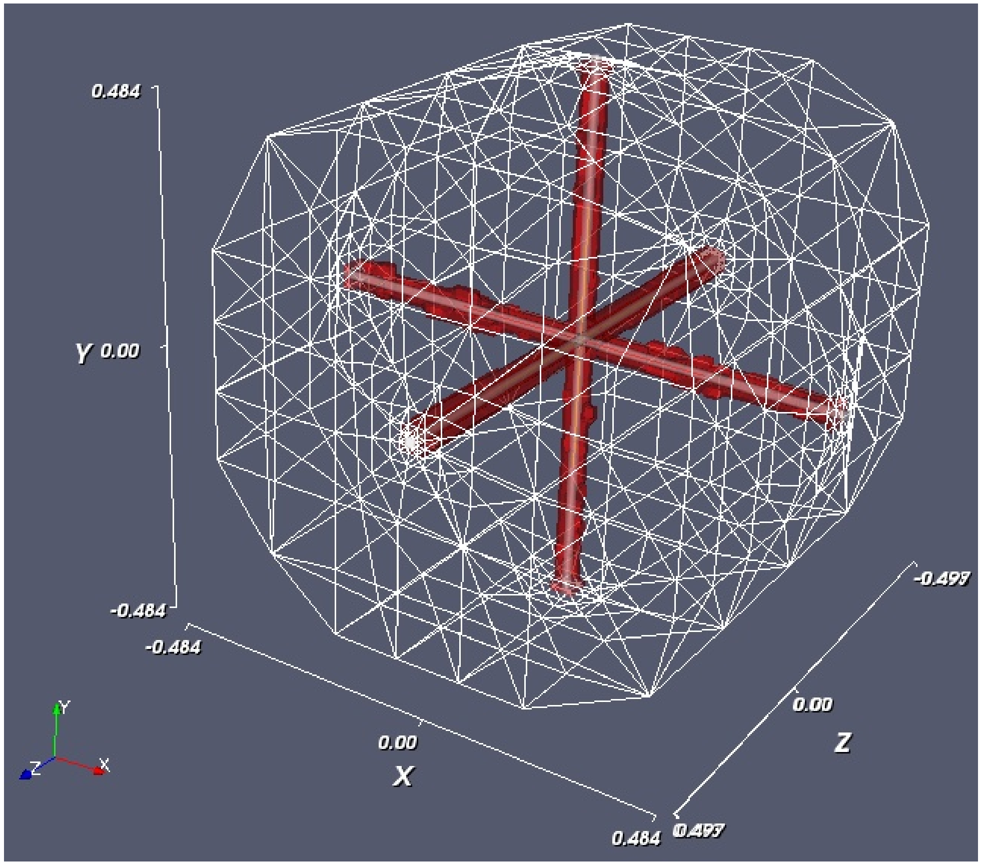
New *ParaView* interface for Geant4 Tracks, Energies, and 3D Mesh Visualization

More examples…

Geant4-generated track and adaptive hexahedral mesh plotted together, using newly developed data interfaces (VTK files)



Adaptive tetrahedral mesh generated for test ion tracks in a cylindrical domain:
- tracks are shown together with energy isosurface (red)
- the mesh is refined in the vicinity of tracks.



APS Photogate Pixel Analysis

So far, APS particle-detectors have utilized only diffusion of charges (electrons and holes) to collect the electrons for readout. It is also illustrated in the figures below, from [Kleinfelder 2004], where in Figure 2 showing the simulated electric profile under the photogate we have indicated that the flat potential profile means no lateral electric field, and hence no drift component of electric current (for charge collection and readout).

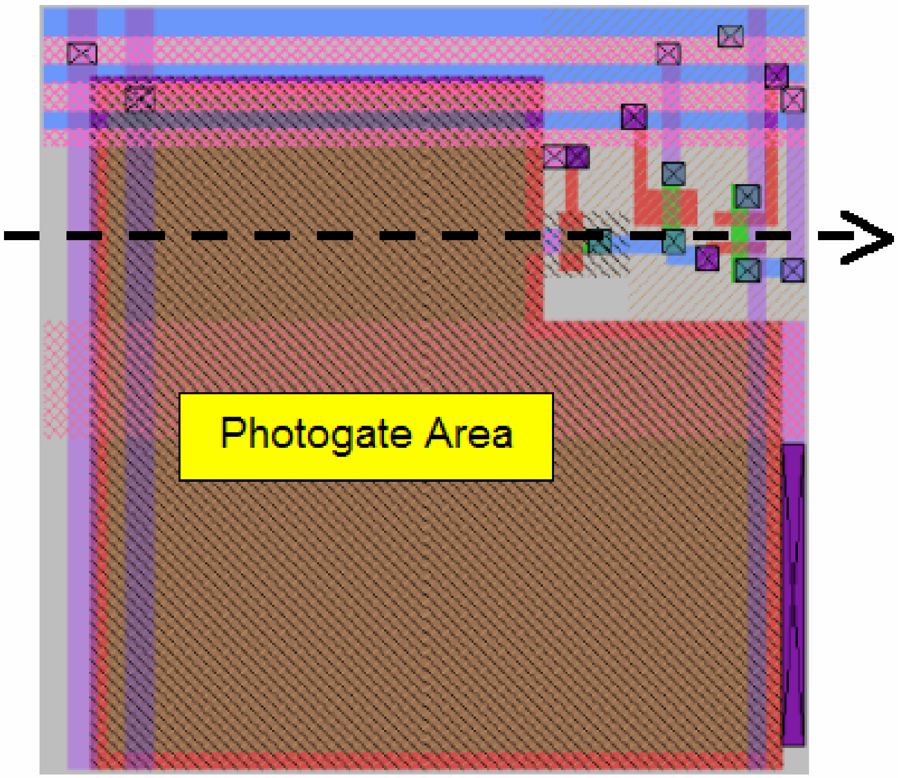


Figure 1. Example photogate pixel layout. The large shape is the photogate, while circuitry in the upper right corner includes the transfer gate, reset and readout transistors [Kleinfelder 2004].

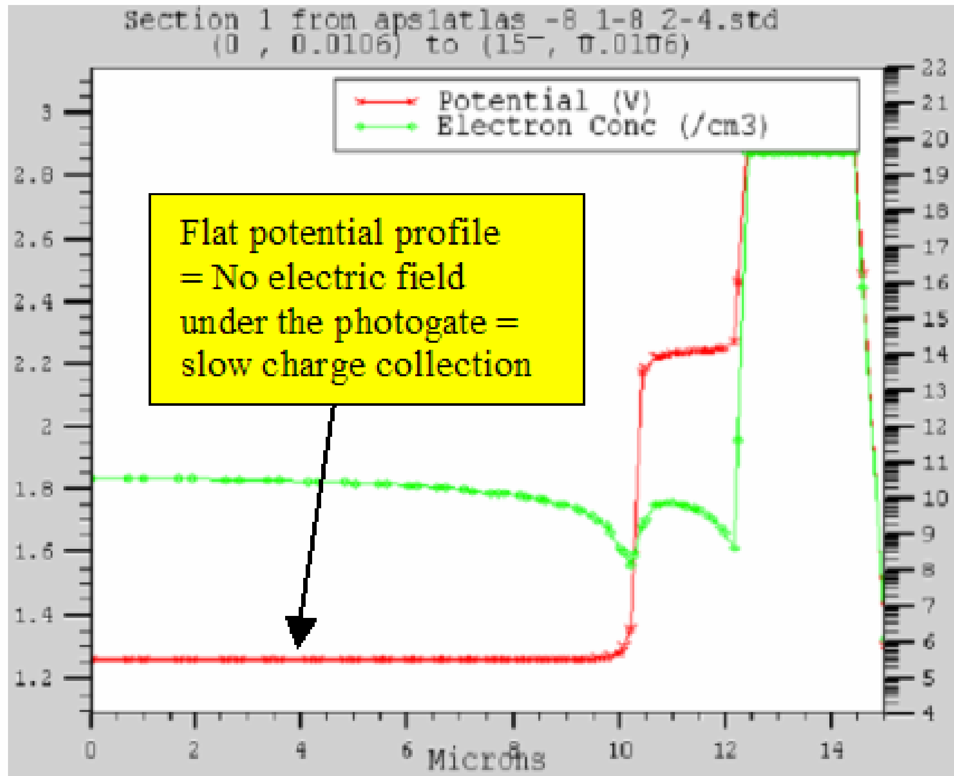


Figure 2. Simulations of potential voltage (red, left scale) and electron concentration (green, right scale) laterally across a photogate (along the dashed black line in Figure 1 [Kleinfelder 2004]. The comment on potential profile is ours.

APS Photogate Pixel Analysis

We propose a **new idea for APS design**: by proper contacts and bias, create **internal lateral electric field** that would force the ***drift*** **component of the electron current**, which is several orders of magnitude faster than the *diffusion* component. This would solve the main problem of current APS detectors – slow readout time (currently ~ 20 ms)!

This new concept is schematically depicted in Figure 3.

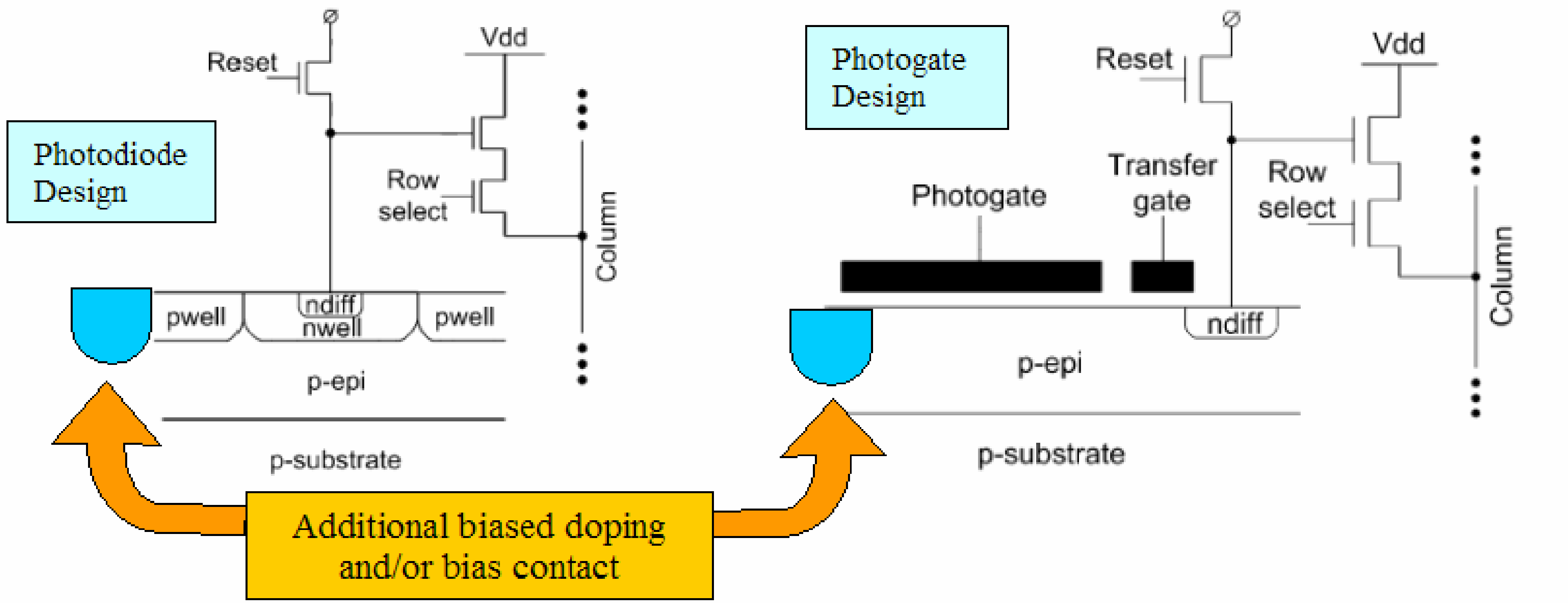
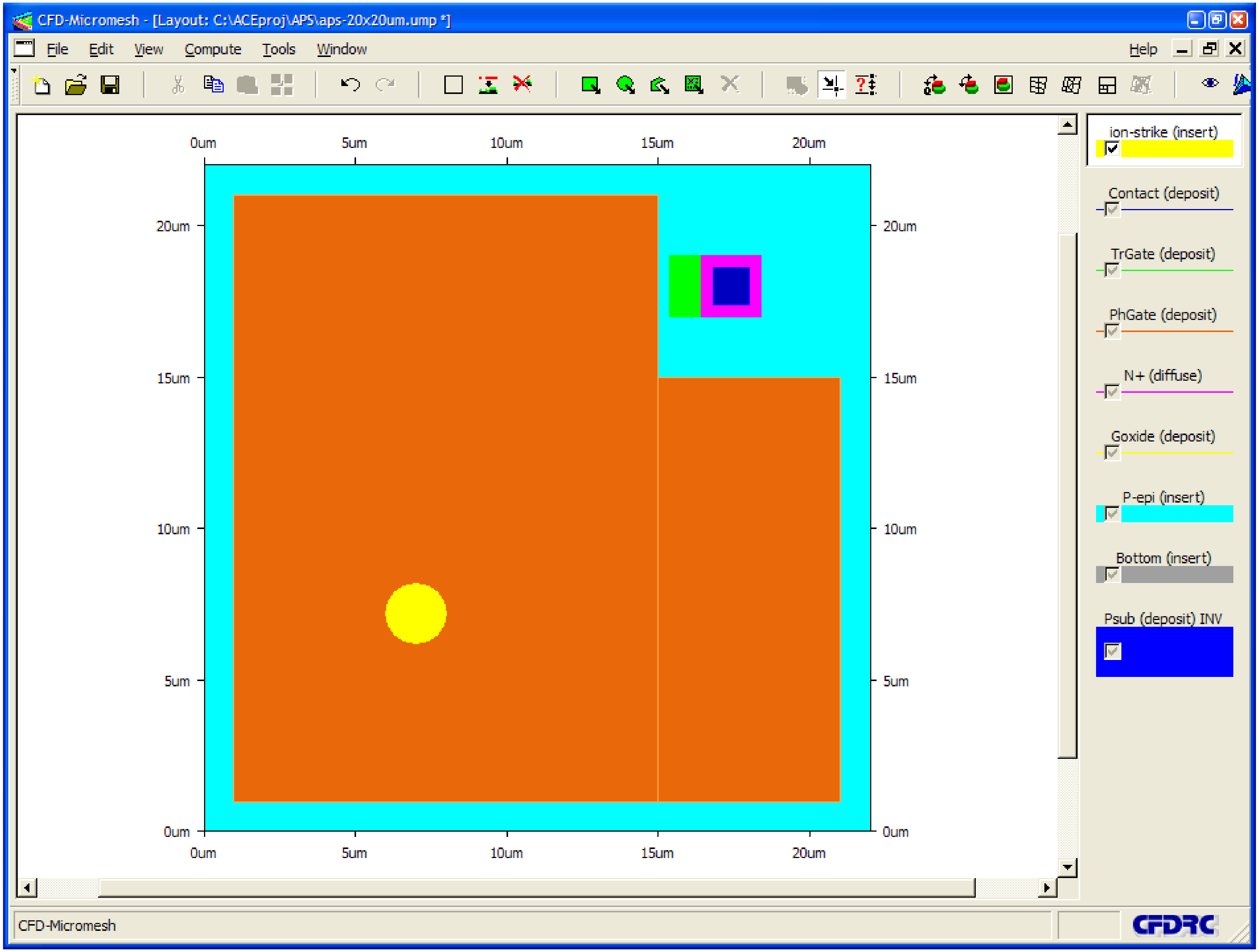


Figure 3. Illustration of the proposed here novel concept of introducing new bias elements into standard APS structures, to create lateral electric field, which will force drift current, and hence faster collection of the charge induced by radiation or ion-strike.

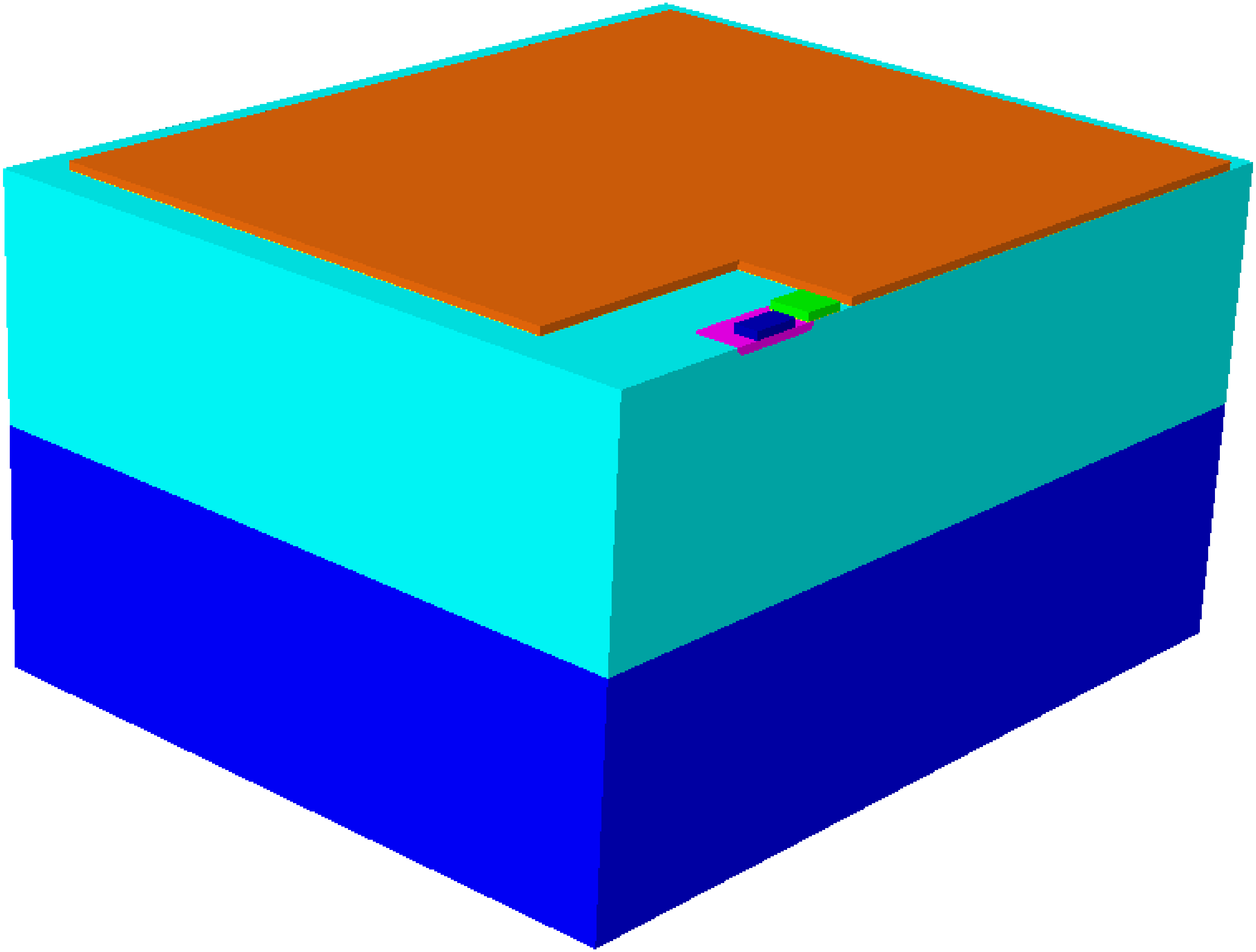
APS Photogate Pixel 3D Modeling

Layout in CFDRC Micromesh tool, for automated 3D model generation:



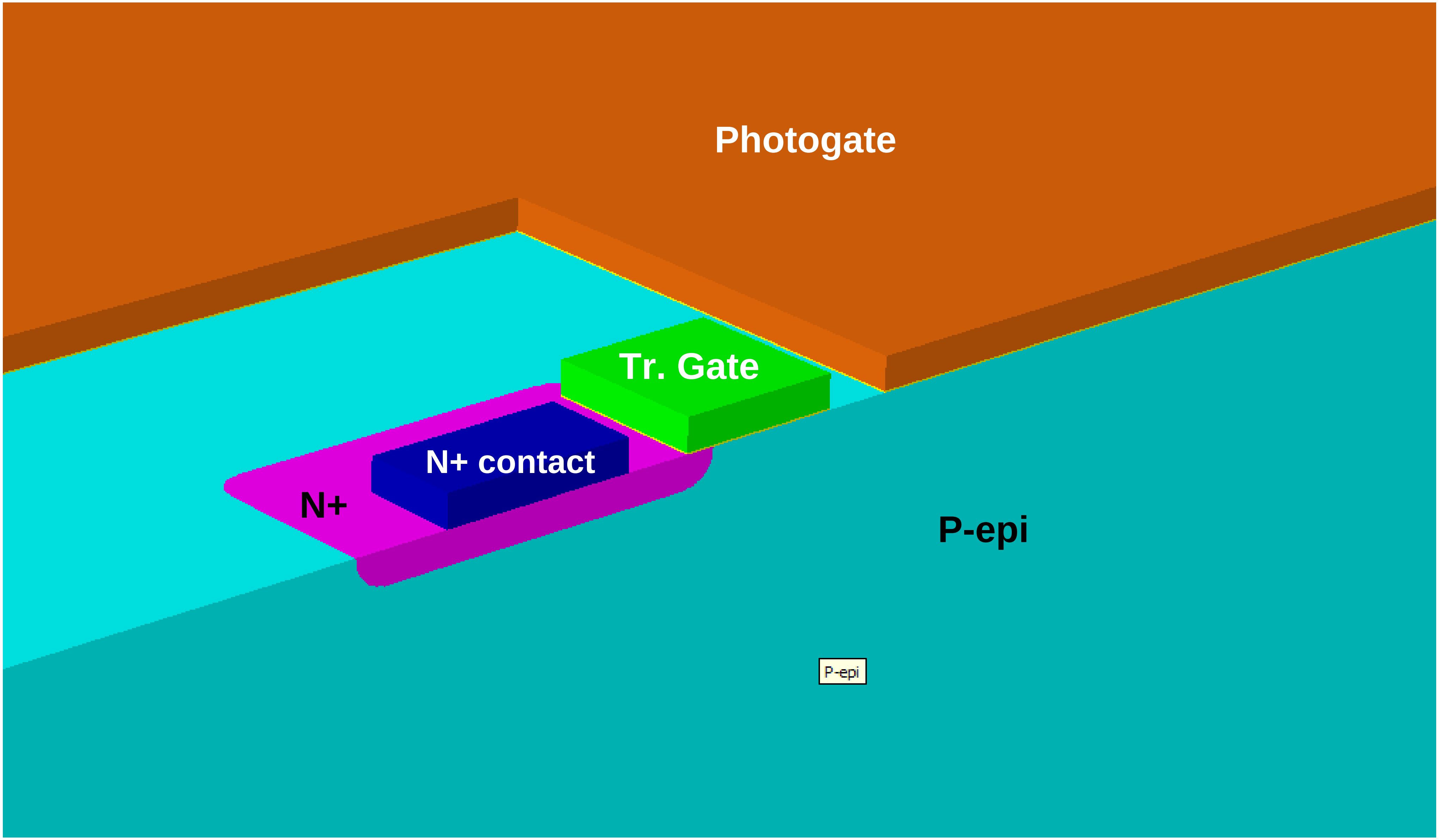
APS Photogate Pixel 3D Modeling

3D model generated with Micromesh:



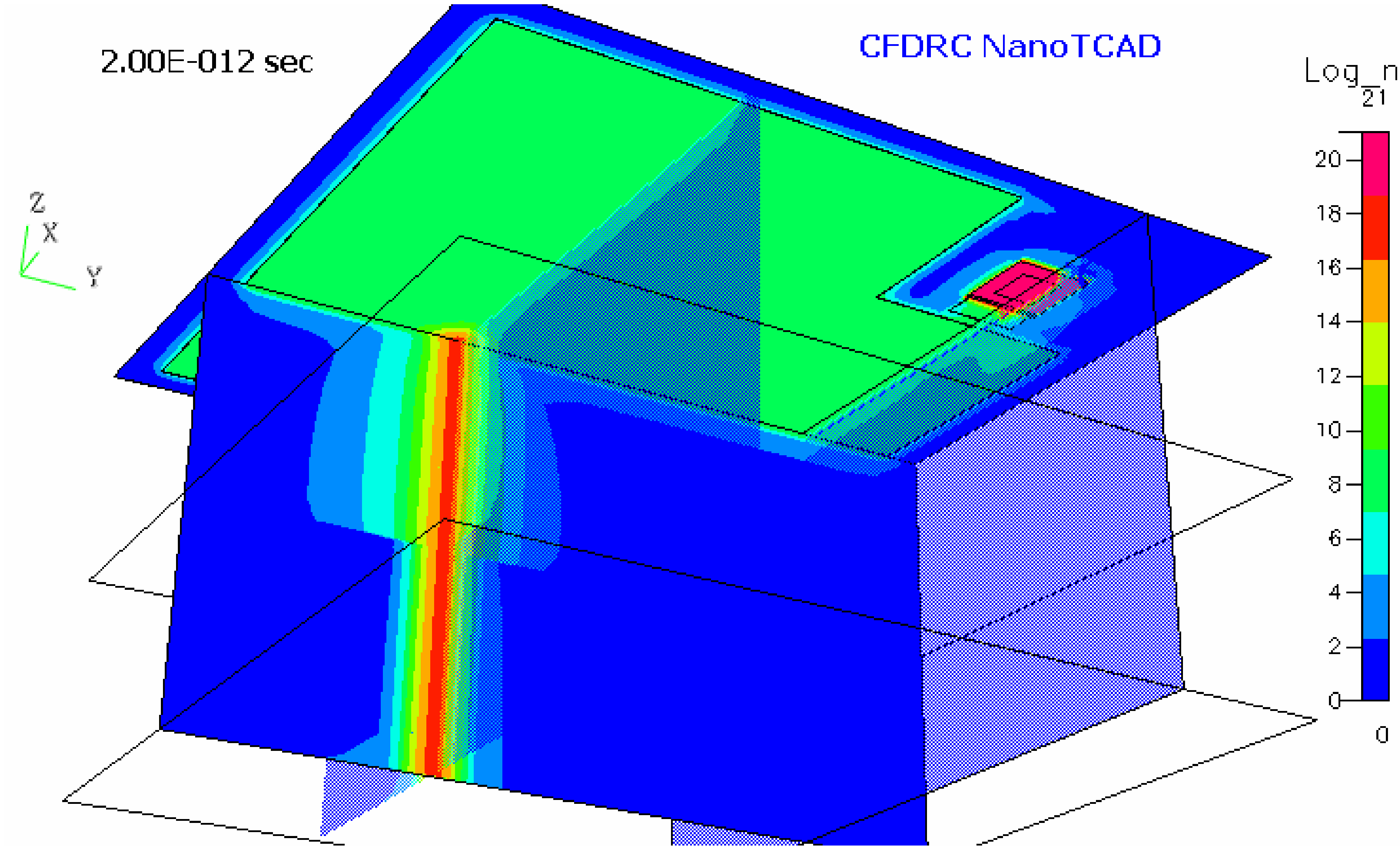
APS Photogate Pixel 3D Modeling

3D model detail:



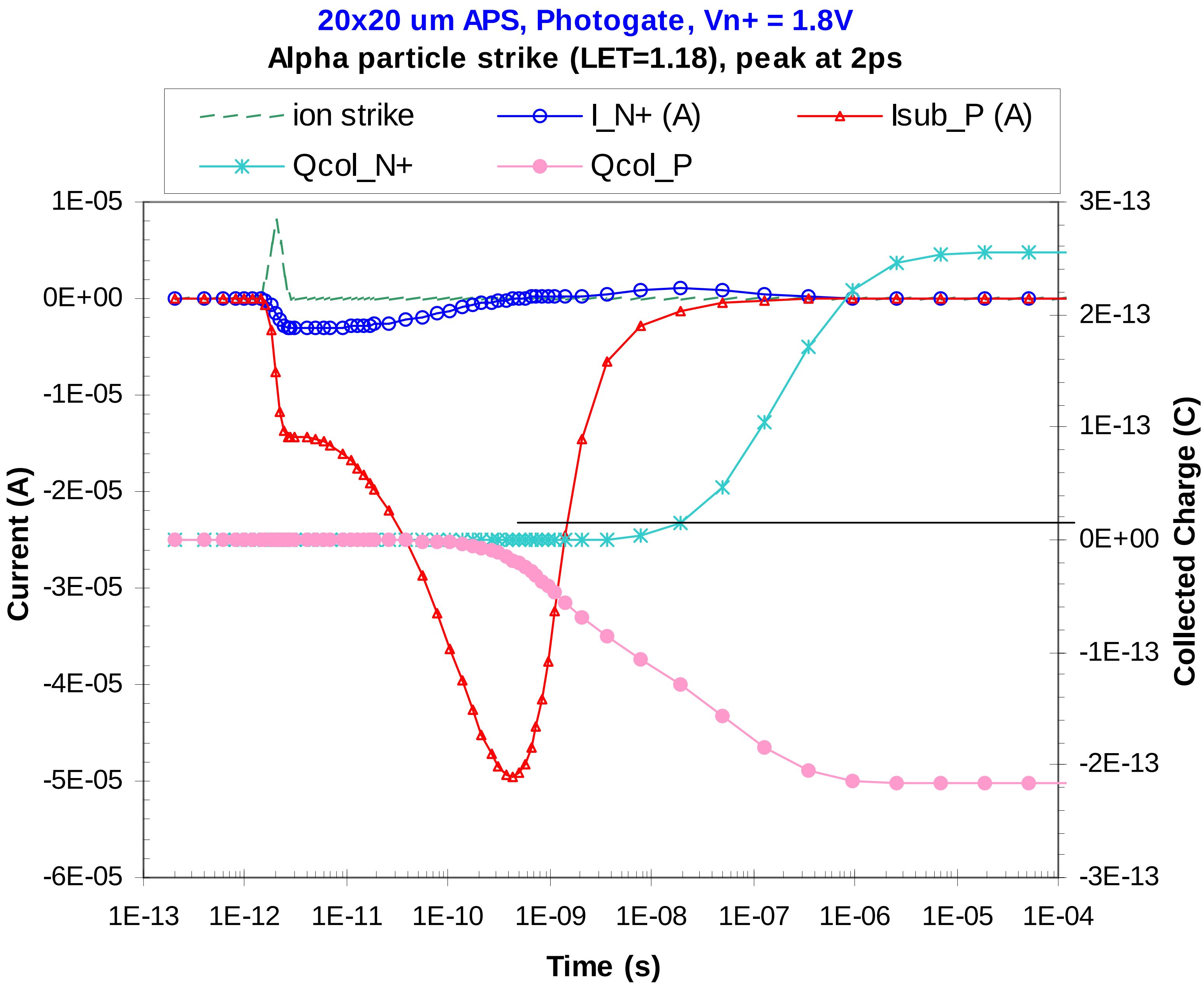
APS Photogate Pixel 3D Modeling

3D transient simulation of ion (alpha particle) strike into photogate area:



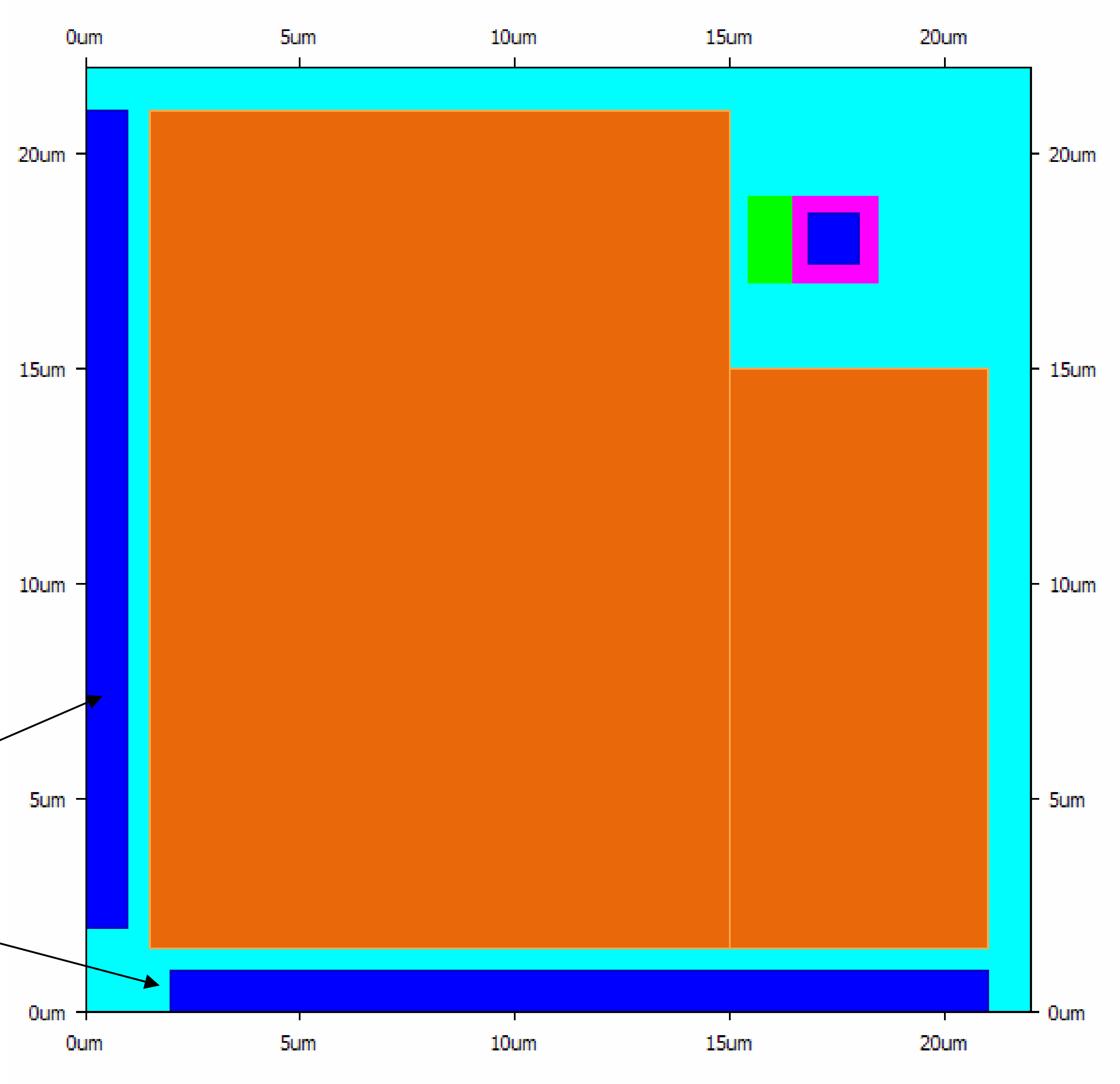
3D transient simulation of ion strike into APS

Currents through the contacts and collected charge:



New APS Photogate Pixel Idea

Layout in CFDRC Micromesh:



Additional
P-epi (substrate)
contacts

Summary and Conclusions

- 3D Modeling and Simulation allows for accurate analysis and exploring of new radiation detectors and device concepts
- LET, an average quantity, does not characterize the range of extreme events.
- Deposited energy and charge have complex microstructure that is relevant to device response.
- Submicron device response is strongly dependent on the microstructure of the radiation event.
- Future single event simulation will require both detailed radiation event simulations and coupled device response computations.
- CFDRC and Vanderbilt are developing an Integrated and Automated **Simulation Environment for Radiation Effects in Next Generation Electronics**